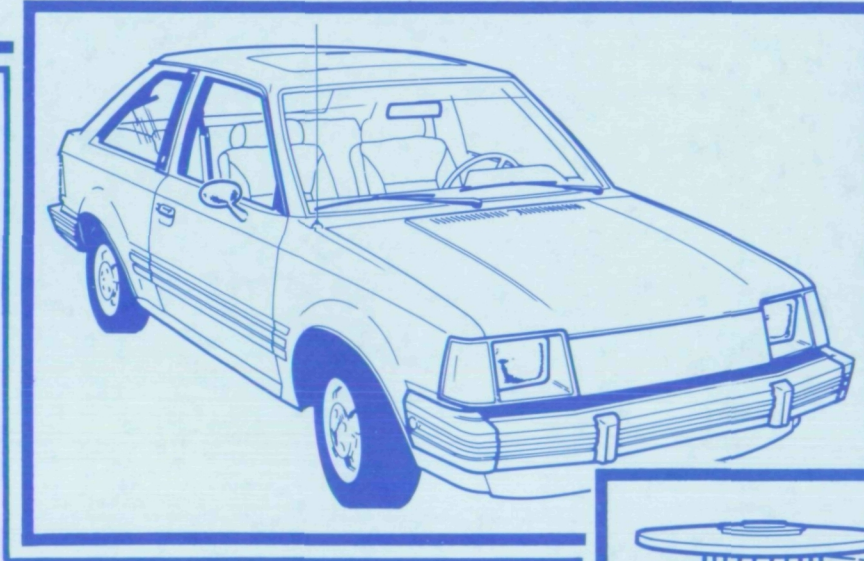
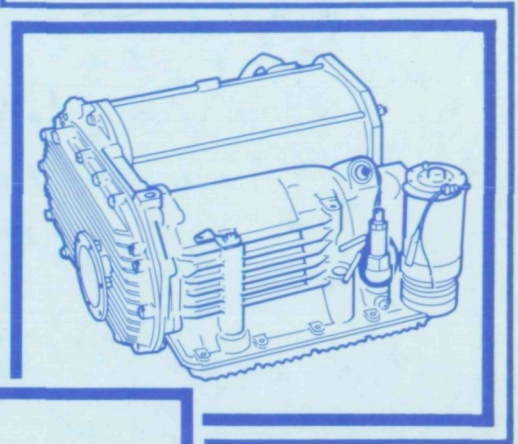
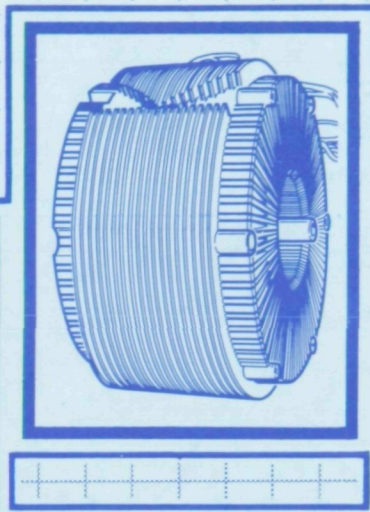
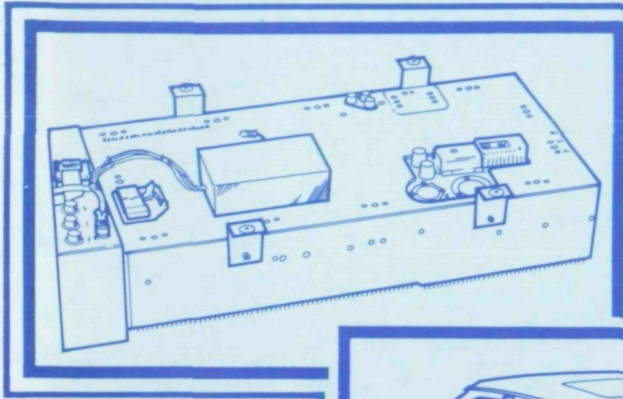


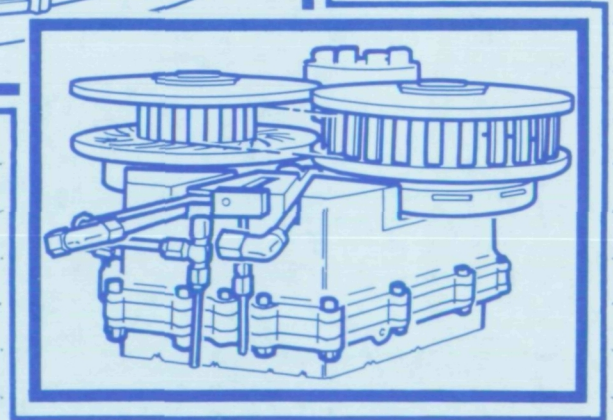
# Electric Vehicle Propulsion Alternatives

DOE/NASA/51044-33  
NASA TM-83504



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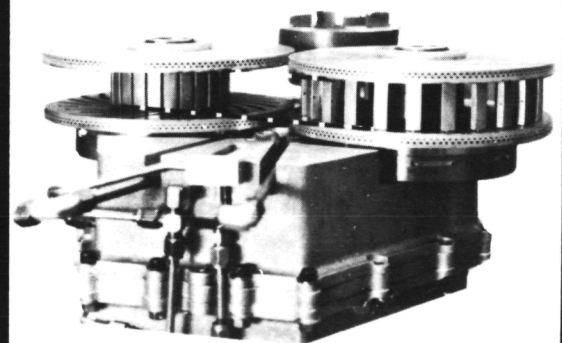
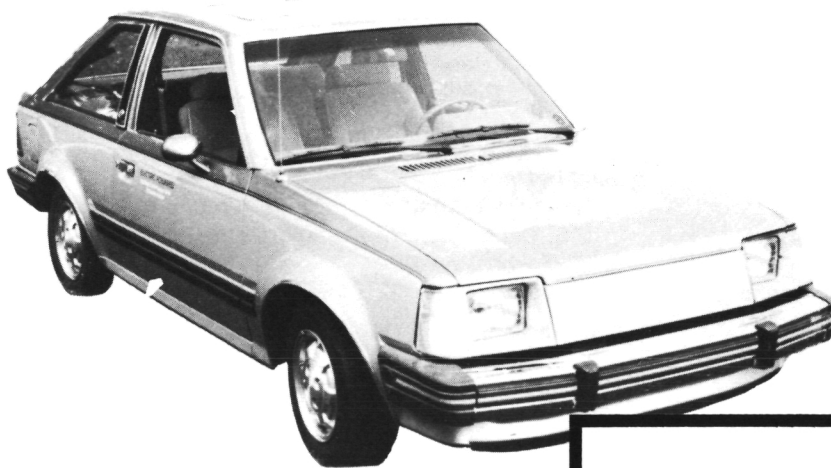
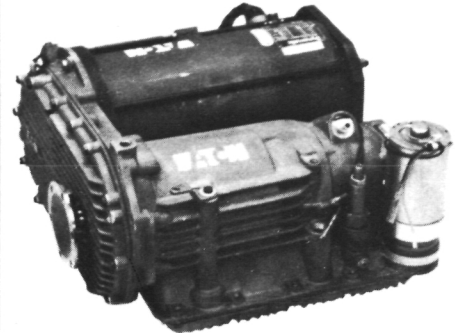
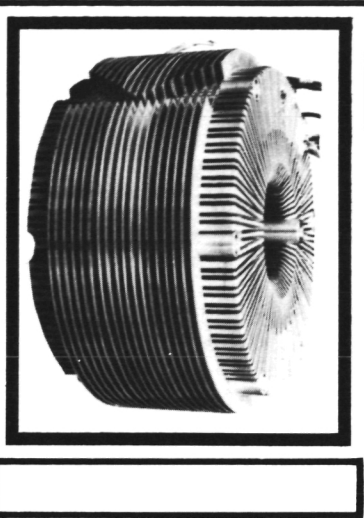
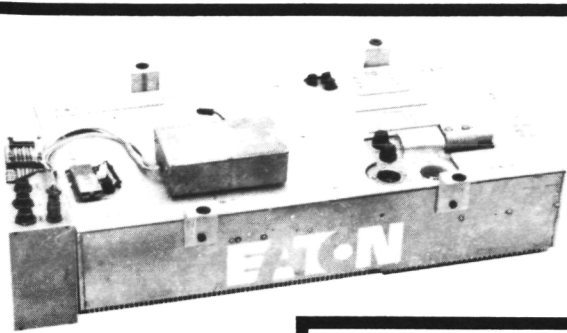
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Prepared for  
U.S. DEPARTMENT OF ENERGY  
Conservation and Renewable Energy  
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Printed in the United States of America

Available from

National Technical Information Service  
U.S. Department of Commerce  
5285 Port Royal Road  
Springfield, VA 22161

NTIS price codes<sup>1</sup>

Printed copy: A04

Microfiche copy: A01

<sup>1</sup>Codes are used for pricing all publications. The code is determined by the number of pages in the publication. Information pertaining to the pricing codes can be found in the current issues of the following publications, which are generally available in most libraries: *Energy Research Abstracts (ERA)*; *Government Reports Announcements and Index (GRA and I)*; *Scientific and Technical Abstract Reports (STAR)*; and publication, NTIS-PR-360 available from NTIS at the above address.

## Executive Summary

The goal of the Electric and Hybrid Vehicle Program of the U.S. Department of Energy (DOE) is to advance technologies for electric and hybrid vehicles in order to enhance their potential as transportation options of national significance. Attainment of the goal may result in a significant number of electric and hybrid vehicles finding their way into the marketplace and ultimately in significant petroleum savings to the nation.

In 1976, the Department of Energy delegated project management of the propulsion system technology development portion of the Electric and Hybrid Vehicle Program to the NASA Lewis Research Center. The subsequent 7 years of propulsion technology development included evaluation of existing commercially available technology, extensive analytical studies, and the development of technology for improved and advanced motors, controllers, transmissions, and complete propulsion systems. The work was accomplished both at NASA Lewis Research Center and by industry and universities operating under contracts and grants.

This report summarizes the Lewis-managed developments. Quantitative data are presented to support the technical generic comparisons of components. The status of technology and future needs are discussed. Costs are addressed generally or relatively because it is not practical to attempt detailed quantitative cost predictions during technology development.

This is intended to serve as a useful, informative, "lessons learned" document that will aid electric vehicle designers in initial selection of system or component approaches. Sufficient tutorial material is included to allow understanding by technical, but nonspecialist, readers.

In this report "electric vehicle" refers to a two- to six-passenger urban car. A few specially designed electric vehicles have appeared recently, either as low-performance vehicles, experimental vehicles, or high-cost, low-volume production vehicles. Many vehicles are conversions of conventional internal combustion engine cars. All of these vehicles are either too costly or generally lack the range and performance necessary for broad public acceptance. The reasons for this are the inadequate energy density, power density, and life of today's practical batteries, the high weight and cost of propulsion systems and components such as motors and controllers, and unacceptably high battery replacement costs.

The propulsion system of an electric vehicle is defined as the integrated set of components that convert electrical energy from the battery to controlled mechanical driving energy at the vehicle wheels. The cost of the propulsion system and the battery have a major effect on the purchase price of an electric vehicle; battery life and cost

have a major effect on vehicle life-cycle cost. As an example, the present original equipment manufacturer's (OEM) cost of a motor-controller combination varies between \$2000 and \$5000. A vehicle set of batteries may cost \$800 to \$2000 depending on the range capability and size of the vehicle. Before commercially successful electric vehicles can be built, the design, performance, and cost of batteries and propulsion components must be improved.

No single approach to a propulsion system will be best for the broad range of potential vehicle missions. Therefore during the first stages of the development of new propulsion components and systems for electric vehicles, parallel efforts have been pursued. As development efforts progress, the number of supported alternatives should be narrowed to those with the greatest potential for low cost and attractive performance.

Although cost reduction is the major goal of propulsion technology development, improved performance through higher power capability, smoother control, and weight reduction is a significant secondary goal. Propulsion system efficiency can also be improved, but the technology available today is already quite efficient although costly. Efforts to further improve efficiency are not practical for some components when the cost-benefit aspect of the needed development is considered. Propulsion system performance can have a direct effect on the battery requirements of an electric vehicle. Because reduced propulsion system weight results in lower vehicle weight, range is increased or less battery power and energy are required for the desired performance and range. Increased propulsion system efficiency has similar effects.

### PROPULSION SYSTEMS

The key item in an electric vehicle propulsion system is the motor because it is the means by which electrical energy is converted to mechanical energy. Controllers condition the electrical energy from the battery and control motor operation. Transmissions match the mechanical output characteristics of the motor to the propulsion needs of the vehicle. For the purpose of this report, electric vehicle propulsion systems are separated into two broad classes: dc and ac. Direct-current systems are based on motors that are designed to operate from a dc source and use brush commutation. Alternating-current systems are based on motor types that normally operate from an ac source but in an electric vehicle are powered from the battery by means of some form of power electronics, such as a dc-to-ac inverter. The advantages of a dc system are mature technology, relatively good efficiency, system simplicity, and, for the present, lower cost than an ac system. Disadvantages of the dc system are somewhat higher weight and, in the future, higher cost than an ac system. The advantages of

an ac motor are low weight, simplicity, high efficiency, low maintenance, and low cost in the long term. The main disadvantage of the ac system is that the power conditioning technology is in the development stage and is not ready for production and wide use.

System voltage affects the life-cycle cost of both the propulsion system and the battery. Increasing the system voltage improves the efficiency and decreases the weight and cost of all of the electrical components of the propulsion system except the battery. Increasing the voltage reduces the energy density and increases the manufacturing cost of lead-acid batteries. From consideration of the life-cycle cost of the combined battery and propulsion system, and safety, propulsion system voltage should be about 100 V for systems using today's technology.

To assess the improvements in propulsion technology, systems of various component makeups were analyzed by using computer simulation to determine the battery power and energy required for each type of system to achieve various ranges and accelerations. Five systems were selected to represent progress in propulsion system concepts since 1976. The systems represent (1) technology of the recent past (1976), (2) currently available components (1982), (3) a benchmark or reference, (4) the best of today's technology, and (5) projections based on technology requiring development.

System 1 represents what could have been built in 1976. It is similar to systems then available from a manufacturer or a converter of internal combustion vehicles into electric vehicles. It is not intended to represent experimental vehicles that had been assembled up to that time. Components are a dc series motor, an armature chopper, and a three-speed automatic transmission with torque converter. These components were selected because of their ready availability and the demonstrated popularity of the automatic transmission.

System 2 represents technology commercially available in 1982. It consists of a dc shunt motor, armature and field choppers, and a three-speed automatic transmission that is more efficient than the 1976 transmission.

The third system, the reference or benchmark of this study, is the propulsion system of the ETV-1, a vehicle developed for the DOE by the General Electric Company (GE) and the Chrysler Corporation. The ETV-1 was conceived, designed, and built to attain specified acceleration, range, and energy consumption objectives. It was selected as the benchmark system because it was designed as an integrated system and because more data are generally available on the vehicle's design and performance than for any other vehicle.

System 4 takes advantage of the best of today's technology. This system is not restricted to off-the-shelf components as are systems 1 and 2 but uses what can be built currently. The system was developed by the Eaton

Corporation with DOE funds and features an ac induction motor with an inverter and controller driving a two-speed automatically shifted transaxle.

The fifth system, which uses flywheel energy storage, promises improved performance over the other systems but requires further development of its components: the electronically commutated motor, the flywheel, and especially the continuously variable transmission that is needed to use the flywheel. The flywheel, which provides sufficient power for quick acceleration, improves performance. With the flywheel providing short-term power boost during acceleration, the drive motor can be sized to provide cruise power efficiently. The flywheel is magnetically coupled to the electronically commutated, permanent magnet motor. The torque output from this combination is transferred through the continuously variable transmission and a fixed reduction gear to the differential.

The five systems were simulated with the aid of a computer program. The computer program, called HEAVY, was developed by Boeing Computer Services under the direction of NASA Lewis. The vehicle characteristics used in the computer simulation are based on the ETV-1 shell with 454 kg (1000 lb) of EV-106 type lead-acid batteries. Vehicle weight was adjusted to account for the effect on vehicle structure of both the reduced battery weight and the weights of the different propulsion systems. Results of the simulation were expressed as vehicle range as a function of battery energy density and as power density from the battery required to accelerate the vehicle from zero to 80 km/h (50 mph) in times ranging from 7 to 40 sec. Vehicle range is the distance traveled following the Schedule D driving cycle of test procedure SAE J227A.

Results of the range calculations show that required battery energy density for a given range has dropped about 40 percent as a result of the propulsion system development represented by systems 3, 4, and 5 as compared with system 1. They also show that the energy losses in the propulsion system have decreased to the point where further reduction of the losses is not practical on a cost-benefit basis. Consequently, any future increases in range should be sought through an increase in energy from the battery.

The results of the acceleration calculations show that systems 3 and 4 can accelerate the test vehicle from zero to 80 km/h (50 mph) in 18 sec. System 5, powered only by the flywheel, can accelerate to the same speed in less than 10 sec. This suggests that system 5 may be used in conjunction with a battery that has high energy density but low power density and so provide both extended range and good acceleration.

System 3 is a dc system; system 4 is ac. Results of the calculations indicate no significant advantage for either system considering either range or acceleration. So,

taking the best of today's technology, dc and ac systems are equal with respect to performance. The same is approximately true with respect to cost. In the future, however, ac systems are expected to have a cost advantage when lower cost solid-state power devices become available.

#### PROPULSION COMPONENTS

During the DOE E&HV program, technologies for motors of low weight and high efficiency have been developed and demonstrated. The technology necessary to design and build very efficient motors has been available for many years, but the predominant factor inhibiting its use has been cost. The recent advances in computer-aided design have allowed optimization of motor designs for specific applications such as the DOE electric test vehicle (ETV-1). The application of newly emerging power electronics technology together with computer-aided design has allowed the consideration and development of motors not previously considered for electric vehicle propulsion. High-speed ac motors, for instance, can now be designed to provide the required performance at high efficiency and with low motor weight. These motors' simplicity, together with their low weight, offer the promise of low system cost. The motor developments of the E&HV program indicate that propulsion motor weights as low as 1 to 2 kg/rated kW (1.6 to 3.3 lb/hp) can now be achieved with ac motors while keeping efficiency about 90 percent. For comparison, present dc motors weigh 4 to 8.5 kg/rated kW (6.6 to 14.0 lb/hp).

As is the case for motors, controller technology development in the DOE E&HV program has resulted in innovative and efficient design concepts for both dc and ac controllers. Controller concepts will continue to be refined to accommodate expected markets. As new power semiconductor devices such as field-effect power transistors and gate-turnoff silicon-controlled rectifiers (SCR's) become available, it is expected that controller designers will take advantage of them if a market is seen. In any event, further development is needed to evolve practical, vehicle-oriented controller packaging concepts.

Clearly, cost is now the major drawback of high-performance ac and dc switch-mode controllers. It must be kept in mind that these controllers contain virtually all of the control functions that are likely to be required for operation of an electric vehicle. The OEM cost of an SCR-based ac controller has been estimated at \$1500 to \$2500. The cost of transistor-based versions of ac controllers is considerably higher now, but they are potentially less expensive because of simpler fundamental circuitry. There is increasing interest by transistor manufacturers in low-cost, high-power transistors. If power transistors with good heat transfer characteristics

were to become available at a price of \$0.15/A, a figure considered to be achievable, transistor-based ac controllers as described here could be produced at an OEM cost of about \$600 per unit. The total cost of an ac motor-controller combination would then be under \$1000 in today's dollars. A dc chopper for motor control will cost considerably less than the ac controllers because the chopper uses fewer power semiconductors. It would not be unreasonable to expect a high-performance dc chopper controller to be of the order of one-half the cost of an ac controller. Of course, a dc motor may be twice as costly as an ac motor. The relative economic attractiveness of the various controller concepts will vary as time and development progress.

Electric vehicles have been constructed without multiratio transmissions, but the lack of low-speed torque multiplication that the multiratio transmission would provide may limit acceleration during starting, passing, and hill climbing. Achieving good low-speed torque without ratio changing requires the use of large motors and more costly controls. Furthermore, using only voltage control with a motor results in less efficient motor operation over the vehicle's driving cycle than that attainable with a variable-ratio transmission. Electric vehicles are energy limited in that they cannot be rapidly refueled as internal combustion engine cars can. Therefore in electric vehicles emphasis must be placed on transmitting energy to the wheels in the most efficient manner while still providing acceptable performance. Present automatic transmissions used in electric vehicles can be a cause of appreciable power and energy loss. More efficient automatic transmissions would hasten the time when electric vehicles become commercially feasible transportation options. Automatically shifted, multiratio transaxles without lossy torque converters have been developed as part of the DOE E&HV program. These transaxles have demonstrated efficiencies in the 90 to 95 percent range and use automotive technology. The results of these development efforts indicate that the technology for high-efficiency, automatically shifted transmissions is ready. Suitable electric vehicle transmissions can be developed for production when a market is identified. In the meantime, they will remain costly because of the need for custom design and low production volume.

A continuously variable transmission (CVT) offers the designer the greatest possible latitude in optimizing the drivetrain. In the case of electric vehicles equipped with flywheels, some form of CVT is needed to continuously regulate the speed, and hence torque, delivered by the flywheel to the drive wheels and vice versa. CVT technology has shown slow but steady progress through the years. Some of the CVT designs reviewed are already nearing the point of commercial acceptance, and undoubtedly there will be improvements with time. However, power limits, cost, and reliability factors are

largely unknown. The belt and traction designs look particularly promising for electric vehicle CVT applications, with belt drives appearing somewhat nearer term.

Energy storage devices such as flywheels or hydropneumatic accumulators are sometimes considered for use in electric vehicles to increase acceleration or range. Since such a device adds to the complexity of a propulsion system, its inclusion must be weighed against using electrical regeneration and increasing the battery weight for additional range or increasing the power capability (and weight) of the propulsion motor and controller for increased acceleration.

In general, cost is the major barrier to wide acceptance of electric vehicles. The ac propulsion systems, though costly today, have the potential of low cost because of the simplicity and low weight of the ac motors. The realization of this potential, however, must await the development of lower cost power semiconductor components and techniques along with compact, integrated, motor-transmission concepts. In the near term, dc-brush-commutated-motor propulsion systems will be less costly than the ac systems and will provide acceptable performance if properly designed.

#### CONCLUDING REMARKS

Since 1976 the NASA Lewis Research Center has been responsible for the propulsion system technology development project of the DOE E&HV program. The subsequent 7 years of propulsion technology development included the evaluation of existing commercially available technology, extensive analytical studies, and the development of technology for improved and advanced motors, controllers, transmissions, and complete propulsion systems. The accomplishments of these activities and their potential effect on the future direction of electric vehicle technology development efforts are thoroughly presented in this report. A brief summary of these accomplishments, a few of the major findings, and their significance follow:

1. In comparing propulsion technology three factors are important: weight, efficiency, and cost.
2. Propulsion component technology advances in motors, controllers, inverters, and transaxles have resulted in component efficiency percentages in the low to mid 90's.
3. Integration of the best of these components into complete propulsion systems has yielded system efficiencies of 75 to 80 percent and represents an efficiency improvement of 30 percentage points over 1976 systems.
4. System weight reductions of approximately 25 percent have been achieved in the past 7 years.
5. These improvements are expected to nearly double

the range of an urban electric car using a given battery.

6. Along with the expected increase in range, these improvements provide an acceleration equivalent to that of a diesel engine car. Further improvement in acceleration will come at the expense of propulsion system efficiency and weight unless flywheel technology is used.

7. Further major efficiency improvements in propulsion systems are not likely, and therefore substantial improvements in vehicle range must come from advances in battery technology.

8. The battery power and energy requirements to achieve various ranges and accelerations for both current and advanced propulsion systems are presented. These results should be useful in establishing battery performance goals for future battery research efforts.

9. Technology development efforts directed at cost reduction were successful. Actual costs must wait until manufacturing cost assessments can be generated that are consistent with the scale and method of production appropriate to the automotive industry.

10. With continued power electronic advances coupled with the ongoing development of inverter systems for both industrial applications and electric vehicles, the cost of an ac propulsion system is expected to decrease to the point that it will become the system choice for advanced vehicles.

## Introduction

The goal of the Electric and Hybrid Vehicle Program of the U.S. Department of Energy (DOE) is to advance technologies for electric and hybrid vehicles in order to enhance their potential as transportation options of national significance. Attainment of the goal may result in a significant number of electric and hybrid vehicles finding their way into the marketplace and ultimately in significant petroleum savings to the nation.

In 1976, the Department of Energy delegated project management of the propulsion system technology development portion of the Electric and Hybrid Vehicle Program to the NASA Lewis Research Center. The subsequent 7 years of propulsion technology development included the evaluation of existing commercially available technology, extensive analytical studies, and the development of technology for improved and advanced motors, controllers, transmissions, and complete propulsion systems. The work was accomplished both at NASA Lewis and by industry and universities operating under contracts and grants.

This report summarizes the Lewis-managed developments. Quantitative data are presented to support the technical generic comparisons of components. The status of technology and future needs are discussed. Costs are addressed generally or relatively because it is not practical

to attempt detailed quantitative cost predictions during technology development.

The information is presented to serve as a useful, informative, "lessons learned" document that will aid electric vehicle designers in initial selection of system or component approaches. Sufficient tutorial material is included to allow understanding by technical, but nonspecialist, readers.

In this report the term "electric vehicle" refers to a two- to six-passenger urban car. A few specially designed electric vehicles have appeared recently, either as low-performance vehicles, experimental vehicles, or high-cost, low-volume production vehicles. Many vehicles are conversions of conventional internal combustion engine cars. All of these vehicles are too costly or generally lack the range and performance necessary for broad public acceptance. The reasons for this are the inadequate energy density, power density, and life of today's practical batteries, the high weight and cost of propulsion systems and components such as motors and controllers, and unacceptably high battery replacement costs.

The propulsion system of an electric vehicle is defined as the integrated set of components that convert electrical energy from the battery to controlled mechanical driving energy at the vehicle wheels. The costs of the propulsion system and the battery have a major effect on the purchase price of an electric vehicle; battery life and cost have a major effect on vehicle life-cycle cost. As an example, the present original equipment manufacturer's (OEM) cost of a motor-controller combination varies between \$2000 and \$5000. A vehicle set of batteries may cost \$800 to \$2000 depending on the range capability and size of the vehicle. Before commercially successful electric vehicles can be built, the design, performance, and cost of batteries and propulsion components must be improved.

No single approach to a propulsion system will be best for the broad range of potential vehicle missions, and many potentially good alternative solutions to a particular mission exist. Therefore during the first stages of the development of new propulsion components and systems for electric vehicles, multiple parallel efforts have been pursued. As development efforts progress, the number of supported alternatives should be narrowed to those with the greatest potential for low cost and attractive performance.

Although cost reduction is the major goal of propulsion technology development, improved performance through higher power capability, smoother control, and weight reduction is a significant secondary goal. Propulsion system efficiency can also be improved, but the technology available today is already quite efficient although costly. Efforts to further improve efficiency are not practical for some components when the cost-benefit aspect of the needed development is considered. Propulsion system performance can have a direct effect

on the battery requirements of an electric vehicle. Because reduced propulsion system weight results in lower vehicle weight, range is increased or less battery power and energy are required for the desired performance and range. Increased propulsion system efficiency has similar effects. Controller operation can influence available battery energy as can the load-leveling effect of energy storage devices such as a flywheel.

There is a wide variety of propulsion system concepts and component types from which a system can be synthesized for a particular set of requirements. To aid in the selection and synthesis of such a system, various system approaches and a study of the effect of new propulsion technology on battery requirements are described in this report. This effect was determined from the results of the evaluations and developments under the Electric and Hybrid Vehicle Propulsion Development Project, which NASA Lewis managed as part of the DOE E&HV program. Also, the generic characteristics, advantages, and disadvantages of the various types of motors, controllers, transmissions, and energy storage devices and their limiting technologies are discussed. Data from the DOE/NASA Lewis Electric and Hybrid Vehicle Propulsion Development Project are included to serve as examples for many of the various concepts discussed.

An early assessment of the state of the art of electric and hybrid vehicles conducted by Lewis in 1976-77 (ref. 1) included road tests of numerous vehicles. This assessment can serve as a baseline against which propulsion improvements can be measured.

## Propulsion Systems

The key item in an electric vehicle propulsion system is the motor because it is the means by which electrical energy is converted to mechanical energy. Controllers condition the electrical energy from the battery and control motor operation. Transmissions match the mechanical output characteristics of the motor to the propulsion needs of the vehicle. For the purpose of this report, electric vehicle propulsion systems are separated into two broad classes: dc and ac. Direct-current systems are based on motors that operate from a dc source and use brush commutation. Alternating-current systems are based on motor types that normally operate from an ac source but in an electric vehicle are powered from the battery by means of some form of power electronics, such as a dc-to-ac inverter.

The variety of dc or ac propulsion systems is quite large. Examination of table I, which is a tabular listing of the various applicable types of motors, controllers, transmissions, and energy storage devices, will verify this variety.

TABLE I. - ELECTRIC VEHICLE PROPULSION SYSTEM COMPONENTS

Controller or power conditioner	Motor	Storage device	Mechanical transmission
Direct current Battery switching Rheostat Chopper Low frequency High frequency Transistor SCR Alternating current Motor-generator sets Inverter <sup>a</sup> Transistor SCR Synchronous polyphase switching plus current and voltage control Transistor SCR	Direct current (brush commutated) Electromagnetic Series Shunt Drum, disk Permanent magnet Drum Disk Alternating current Induction Squirrel cage Wound rotor Synchronous Electromagnetic excitation Drum Disk Permanent magnet Drum Disk Unexcited Drum Disk	Hydraulic Elastomeric Flywheel	Fixed ratio Multiple discrete ratios Automatic Manual Continuously variable Torque converter automatic

Electrical  
energy  
source

Drive  
wheels

<sup>a</sup>Variable frequency and voltage.

#### GENERAL SYSTEM CHARACTERISTICS

Most dc systems have a series or shunt motor whose speed is usually 5000 rpm or less. Power conditioning is usually accomplished by battery configuration switching or by a power electronic switch-mode controller, commonly called a chopper. The advantages of a dc system are mature technology, relatively good efficiency, system simplicity, and, for the present, lower cost than an ac system. Disadvantages of the dc system are somewhat higher weight and, in the future, higher cost than an ac system. Lead time for mass production of ac motors should be considerably less than that for dc motors in ratings suitable for electric vehicles.

An ac system may have an induction motor or a synchronous motor. Motor speed is usually above 8000 rpm. Power conditioning is usually accomplished by a combined inverter-chopper. The advantages of an ac system are low weight, a simple motor, high efficiency, low motor maintenance, and low cost in the long term. The ac system power-conditioning technology is still in the development stage.

Electric propulsion technology has reached a high level of refinement in the area of efficiency. Weight and cost, however, need improvement before electric vehicle propulsion can reach its potential as a viable alternative to internal combustion engine propulsion for passenger automobiles. Technology developments in electric propulsion that resulted from the DOE E&HV program indicate that cost and weight can be reduced and that efficient, low-cost, lightweight propulsion systems for

electric vehicles will be economically viable if the present downward trend in semiconductor power electronics cost continues.

#### SYSTEM VOLTAGE CONSIDERATIONS

Recent studies of advanced electric propulsion systems (refs. 2 and 3) indicate that system voltage affects the life-cycle cost of both the propulsion system and the battery. Increasing the system voltage improves the efficiency and decreases the weight and cost of all of the electrical components of the propulsion system except the battery. Increasing the voltage reduces the energy density and increases the manufacturing cost of lead-acid batteries.

#### Components Other Than the Battery

The electric vehicle industry is not a mature industry. Components are usually designed and built for other purposes and adapted to electric vehicles. Consequently, there are no test or experimental data readily available from manufacturers that relate efficiency, cost, or size of components to system voltage. To obtain such voltage-related data, we relied on theoretical considerations, discussions with manufacturers, and review of industrial and commercial practices. The resulting estimates are independent of a particular propulsion system and so apply to all types of systems. Estimates of the effect of voltage on cost and efficiency for electric motors are shown in figures 1 and 2. Figures 3 and 4 show how system voltage affects the cost and efficiency of power-handling devices, choppers, and inverters.

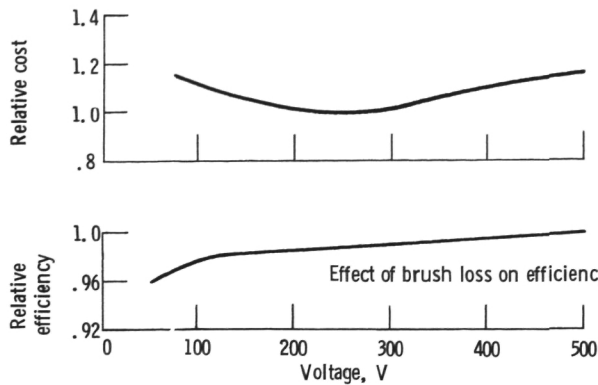


Figure 1. – Estimated cost and efficiency of dc motors as a function of voltage.

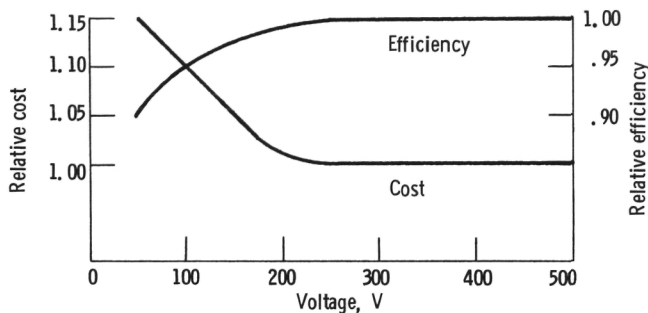


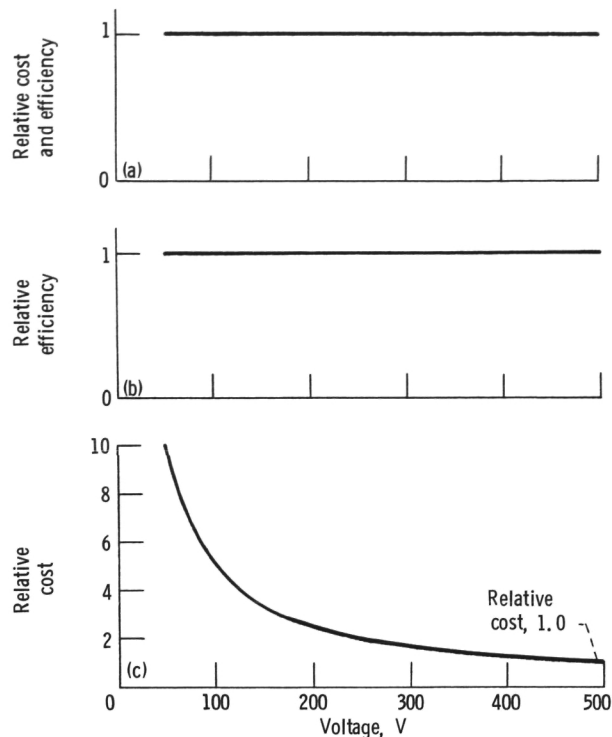
Figure 2. – Estimated cost and efficiency of ac induction motors as a function of voltage.

## Batteries

Characterization of the lead-acid batteries was done by Eagle-Picher Industries, Inc., as a subcontractor to the AiResearch Manufacturing Company. Some of the results of the study are shown in figure 5. Battery costs increase linearly with voltage up to about 350 V due to the increasing number of cells in the battery. Above 350 V the increase in the number of cells is offset by the reduced number of plates, and the cost becomes fairly constant. Mass specific energy, in watt-hours per kilogram, decreases by 10 to 15 percent from 50 to 500 V and volumetric energy density, in watt-hours per liter, decreases by 20 to 30 percent.

## Safety

Information from the National Safety Council (ref. 4) indicates that a 500-V dc system will produce the same biological effects as the commercial 115-V, 60-Hz system. Both systems are extremely dangerous. A 50-V dc system is less hazardous than a 500-V dc system for identical conditions of body contact and grounding. However, we must assume that battery charging and maintenance will be performed when the vehicle is wet and covered with a film of salt. Under these conditions a 50-V dc system has the potential for fatality and so is no less hazardous than a 500-V dc system.



(a) Shunt-field controller.

(b) Stepped-voltage controller.

(c) Stepped-voltage controller and cable, connectors, and other power handling equipment.

Figure 3. – Estimated cost and efficiency of power-handling devices as a function of voltage.

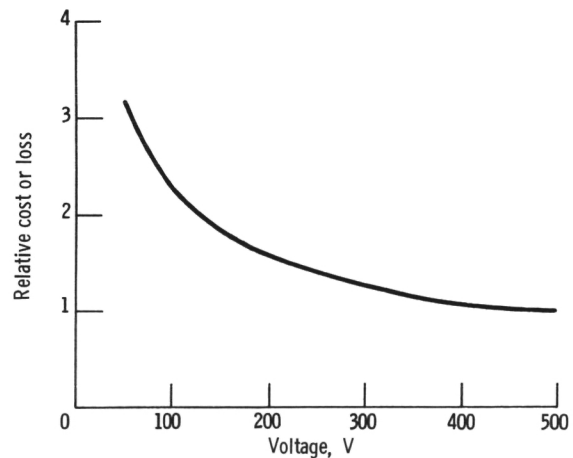


Figure 4. – Estimated costs or losses for choppers and inverters as a function of voltage.

The National Electrical Code classifies systems as below 300 V, between 300 and 600 V, and above 600 V. In general, safety considerations become more restrictive as voltage increases. These classifications indicate that system voltages probably should be restricted to less than 300 V.

From consideration of the life-cycle cost of the combined battery and propulsion system, and safety,

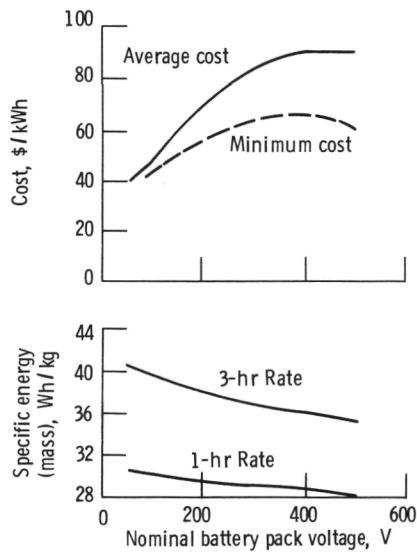


Figure 5. — Estimated cost and specific energy of lead-acid batteries as a function of voltage.

propulsion system voltage should be about 100 V for systems using today's technology.

#### PROPULSION SYSTEM SYNTHESIS

The range of an electric vehicle is limited primarily by the onboard energy source, the battery. To assess the effect of propulsion technology on battery requirements, systems of various component makeups were analyzed by using computer simulation in order to determine the battery power and energy required for each type of system to achieve various ranges and accelerations.

Five conceptual propulsion systems were analyzed. The propulsion system is considered to be that part of the drivetrain between the battery output and the drive wheels. In general, the propulsion system includes the controller, the motor, and the transmission and differential or the transaxle. Systems were selected to represent progress in propulsion system concepts since 1976, when Congress put electric vehicle development into public law. The five systems are shown in figure 6. The systems represent, respectively, (1) technology of the recent past (1976), (2) currently available components (1982), (3) a benchmark or reference, (4) the best of today's technology, and (5) projections based on technology requiring development.

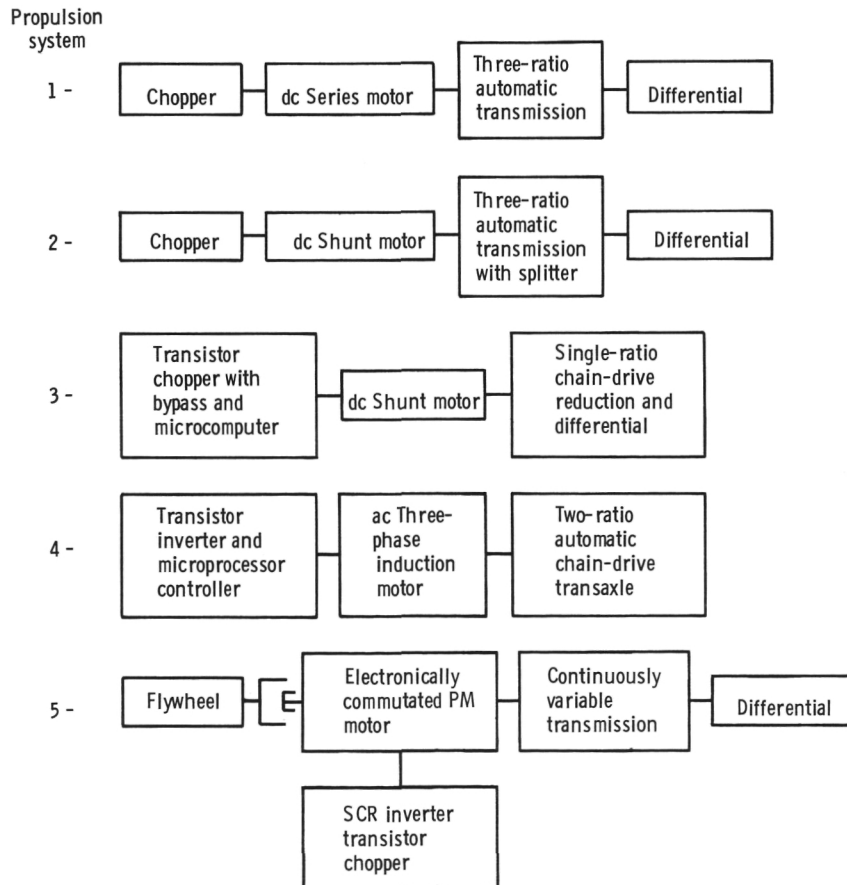


Figure 6. — Propulsion system concepts.

System 1 represents what could have been built in 1976. It is similar to systems then available from a manufacturer or from a converter of internal combustion vehicles into electric vehicles. It is not intended to represent experimental vehicles that had been assembled up to that time. Components are a dc series motor, a low-switching-frequency (below 500 Hz) armature chopper, and a three-ratio automatic transmission with a torque converter. These components were selected because of their ready availability and the demonstrated popularity of the automatic transmission.

System 2 represents commercially available technology of 1982. It consists of a dc shunt motor, a low-frequency armature and field chopper, and a three-ratio automatic transmission that is more efficient than the 1976 transmission. This transmission has an internal splitter gear that transmits some engine torque directly to the differential in second and third gears. This reduces torque converter losses and improves the efficiency of the transmission.

The third system, the benchmark or reference of this study, is the propulsion system from the ETV-1, a vehicle developed for the DOE by the General Electric Company and the Chrysler Corporation. The ETV-1 was conceived, designed, and built as an integrated approach to a complete electric vehicle that would attain DOE-specified acceleration, range, and energy consumption objectives. Its propulsion system consists of a dc shunt motor, a microcomputer-based control system, and single-ratio gear reduction with chain drive to the differential. This propulsion system was selected as the benchmark system for two reasons: first, because it was designed as an integrated system and, second, because more data are generally available on this vehicle's design and performance than on any other vehicle.

System 4 takes advantage of the best of today's technology. This system is not restricted to off-the-shelf components as are systems 1 and 2 but uses what can be built currently. The system was developed by the Eaton Corporation with DOE funds and features an ac induction motor with an inverter and controller driving a two-speed automatic transaxle.

The fifth system consists of an electronically commutated, permanent magnet motor, a flywheel, and a continuously variable transmission (CVT). It promises improved performance over the other systems but requires further development of the motor, the flywheel, and especially the CVT. Improved performance results from the flywheel, which provides sufficient power for quick acceleration. With the flywheel providing short-term power boost during acceleration, the drive motor can be sized to provide cruise power efficiently. The electronically commutated permanent magnet motor is magnetically coupled to the flywheel. The torque output from this combination is transferred through the steel V-belt CVT and a fixed-reduction gear to the differential.

## Analysis

The five conceptual propulsion systems just described have been analyzed using computer simulation. The analysis has been directed toward comparing the performance of the five systems and showing how evolving technology affects traction battery requirements.

**Approach.** – The aim of the analysis was to determine, for each of the five propulsion systems, the time to accelerate a vehicle from zero to 80 km/h (50 mph) and the range of the vehicle over the Schedule D driving cycle of test procedure SAE J227a. The vehicle energy source is a 454-kg (1000-lb) battery (0.28 mass fraction). The ETV-1 shell was selected as the test vehicle for the analysis. Its characteristics used in the simulation are shown in table II. The actual curb weight used in the simulation varied with the weight of the propulsion system. A factor of 1.3 was used to account for the effect of the five different propulsion system weights on vehicle structure weight.

The simulations were run by using the HEAVY computer program. It is described in a following section, "HEAVY simulation program." The simulation used the fractional utilization model for the battery to determine vehicle range. Battery characteristics assumed are discussed later in the section on simulation.

**Constraints and assumptions.** – The following constraints were imposed on the simulation:

- (1) The ETV-1 structure weight was reduced for the 454-kg battery weight.
- (2) The battery was a golf-cart lead-acid type.
- (3) Each vehicle was to be capable of diesel-equivalent performance (i.e., acceleration from zero to 48 km/h (30 mph) in 8 sec and acceleration from 40 to 88 km/h (25 to 55 mph) in 16 sec).
- (4) Minimum top speed was 97 km/h (60 mph).
- (5) Schedule D of SAE J227a was used for range calculation.
- (6) The fractional utilization battery model was used for range calculation.
- (7) The shift schedule was set for maximum energy efficiency during acceleration from zero to 88 km/h.

Use of the ETV-1 with a 454-kg battery as the working vehicle was mutually agreed on by DOE and Lewis. The

TABLE II. – ETV-1 VEHICLE CHARACTERISTICS

Curb weight <sup>a</sup> , kg (lb)	1468 (3237)
Battery weight, kg (lb)	454 (1000)
Payload, kg (lb)	136 (300)
Frontal area, m <sup>2</sup> (ft <sup>2</sup> )	1.79 (19.3)
Coefficient of drag	0.3
Coefficient of rolling resistance	0.011 (0.011)
kg/kg (lb/lb)	
Wheel radius, m (ft)	0.28 (0.92)

<sup>a</sup>Includes battery but no payload.

lead-acid golf-cart battery voltage characteristics were chosen after unsuccessful attempts by Lewis to obtain characteristics for other electric vehicle batteries. We were not able to obtain sufficient data for the voltage-current characteristics for any other battery in enough detail to construct models for the computer simulation. There is a need for these data if electric vehicle simulation by computer is used for design studies and performance comparisons.

**HEAVY simulation program.** — HEAVY (Hybrid and Electric Advanced Vehicle Systems) is a computer program that predicts the performance of an electric or hybrid propulsion system. It was developed for the DOE by Boeing Computer Services Company under the direction of Lewis. Its description and use are detailed in references 5 and 6.

HEAVY is intended for use early in the design process for concept evaluation, alternatives comparison, component sizing, etc. The user defines the system to be simulated by using the program's library of predefined component models. Or the user may modify a model or create a new one. The model generation part of HEAVY connects the user-specified components to form a model of the complete vehicle and retrieves specified information for display. Diagnostic information, the amount of which is user controllable, is available at this point. After judging the model generation results to be correct, the user uses the simulation part of HEAVY to execute the prepared model and to deliver output in user-specified quantity and format. Graphic and tabular output are available.

Components are modeled with their steady-state characteristics, either by equations or by data maps. HEAVY deals with long-term system dynamics such as vehicle speed, distance traveled, and shaft speed rather than component transients such as shaft flexing. It transfers torque and shaft speed or voltage and current from component to component. And it predicts vehicle performance under conditions of limited component resources such as battery voltage or electric machine torque.

**Simulation.** — The method that the HEAVY program uses to simulate a propulsion system is simple. From a user-supplied velocity-time profile for the vehicle, the program calculates a drive-wheel torque and speed from road-load equations to meet the velocity profile. The torque request is sent back through the differential and the transmission, after accounting for appropriate torque losses, to the output of the motor. The motor component processes this request into a current request from the controller, which, in turn, requests an appropriate current from the battery. The battery component returns a voltage and current response to the controller, and the process continues until the torque and speed response converges to a value that either satisfies the velocity-time

profile or exhausts the energy available to propel the vehicle.

This simulation method requires that the battery component have voltage-current data to respond to the current request from the motor. When we searched for these data for different kinds of batteries, we found that the only battery that has enough voltage-current data to permit computer modeling is the EV-106 lead-acid battery.

A secondary objective of this study is to show how vehicle range depends on battery energy density. Early in the study we intended to vary battery energy density by using different types of batteries with widely different energy densities. But because of the lack of voltage-current data for other battery types, we confined the study to the lead-acid battery. We were able to vary battery energy density analytically by adjusting the Ragone plot (power density vs energy density) to provide different energy densities for a given power density. It follows then that a display of vehicle range versus battery energy density applies to a fictional battery with the EV-106 voltage-current characteristics and power density-energy density characteristics.

To provide some variation in voltage-current characteristics, we used the concept of a soft and a stiff battery. The soft battery has voltage-current characteristics typical of the EV-106 battery at depths of discharge from zero to 100 percent. As used in this study the stiff battery has a constant voltage for any discharge current. See figure 7. This treatment of the lead-acid voltage-current characteristic then will show the effect of the extremes and so allow estimation of the effects of batteries that have voltage-current characteristics between the extremes.

Component models for the five systems are based largely on experimental data. For system 1 (1976) experimental data for the series motor and the controller were obtained from tests conducted for Lewis by the Eaton Corporation (ref. 7). The General Motors automatic transmission was also characterized from data obtained by the Eaton Corporation (ref. 8).

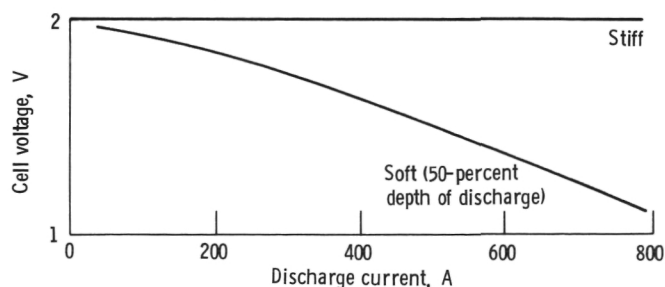


Figure 7. — Voltage-current characteristics of stiff and soft lead-acid batteries.

For system 2 (1982) the shunt motor data were obtained from the General Electric Company (private communication from F. DeWolf). Controller data were derived from data in reference 5. The Eaton Corporation (ref. 9), under Government contract, provided the experimental data for the Ford automatic transmission.

For the benchmark system, system 3, the data for the shunt motor were obtained from the same source as for the shunt motor of system 2. The control system data are based on measurements (ref. 10) made with a laboratory model of the control system by the General Electric Company. Data for the single-ratio reduction gear with chain drive to the differential are based on tests done at Lewis (ref. 11).

System 4 component data were based on Eaton Corporation measurements of the ac propulsion system reported in reference 12.

System 5 component data were obtained from several sources. Data for the electronically commutated permanent magnet motor and the inverter and controller were based on measurements by the Garret-AiResearch Manufacturing Company reported in reference 13. Flywheel loss characteristics were based on windage and bearing loss information provided by Lewis (ref. 14). Data for the CVT were obtained from an engineering design study by the Battelle Memorial Institute (ref. 15). The weight allowance for the flywheel component was 68 kg (150 lb), the flywheel was sized at 0.9-MJ (250-Wh) usable capacity for operation at 26 000 rpm. For this size flywheel the weight allowance accommodates either a high-strength steel wheel or a low-speed composite wheel.

In general, the data for motors and controllers had to be scaled to a somewhat higher power level (table III).

TABLE III. - COMPONENT SCALING

Propulsion system	Component <sup>a</sup>	System voltage <sup>b</sup> , V dc	Original rating		Scaled rating	
			kW	A	kW	A
1	M	164	24	---	27	---
	PC		----	450	---	450
2	M	108	15	---	23	---
	PC		----	450	---	465
3	M	108	15	---	22	---
	PC		----	400	---	400
4	M	144	18.6	---	24	---
	PC		30	---	39	---
5	M	108	15	---	(c)	---
	PC		26	---	(c)	---
	Flywheel		<sup>d</sup> > 75	---	(c)	---

<sup>a</sup>M = motor; PC = power conditioner.

<sup>b</sup>System voltage set by motor voltage requirements.

<sup>c</sup>System 5 was not scaled because flywheel is used for acceleration. This system provides more power than is needed for diesel-equivalent acceleration.

<sup>d</sup>Five-second rating.

Motor weight varied directly with rated torque; motor losses varied directly with rated power. Controller weight varied directly with maximum current; controller losses varied directly with maximum power. For all of the systems except system 4 the peak torque was set at twice the continuous rating. Reference 12 states that the peak-to-continuous torque rating of the induction motor of system 4 is 1.6.

Because the ratings of the transmissions for all of the systems were judged to be satisfactory for the diesel-equivalent acceleration, the transmission data were used without scaling.

Drive motor size was estimated in a consistent manner for all five systems. The motor size was set to give the torque required for the most demanding of the diesel-equivalent accelerations, viz, 40 to 88 km/h (25 to 55 mph) in 16 sec. The maximum current that was required from the controller to get this motor torque established the controller size.

Component weights for all of the systems are listed in table IV.

## Results

Figures 8 and 9 show the effect of the different propulsion systems on the energy density and the power density required from the battery. The propulsion system designated X is the same as system 3, the benchmark system, except that all components of system X are lossless (100 percent efficient). System X can be used to determine the road losses (drag and rolling resistance) of the vehicle.

The information in figure 8 can be interpreted from two points of view. At a given range, say, 121 km (75 miles), battery energy required has dropped from about 70 Wh/kg (32 Wh/lb) to about 40 Wh/kg (18 Wh/lb) from system 1 to systems 3, 4, and 5. On the other hand, for a battery energy of 40 Wh/kg the development of propulsion systems from system 1 to systems 3, 4, and 5 has increased available range from 64 to 121 km (40 to 75 miles). Note that the plot of figure 8 requires that the

TABLE IV. - COMPONENT WEIGHT

Propulsion system	Motor		Controller		Transmission		Total	
	Weight							
	kg	lb	kg	lb	kg	lb	kg	lb
1	122	269	24	53	<sup>a</sup> 101	<sup>a</sup> 223	248	547
2	148	326	52	115	<sup>a</sup> 110	<sup>a</sup> 243	310	683
3	142	313	48	106	42	93	232	511
4	75	165	59	130	51	112	184	406
5	16	35	68	150	<sup>a,b</sup> 182	<sup>a,b</sup> 401	266	586

<sup>a</sup>Weight includes weight of differential, 44 (97), for systems 1, 2, and 5.

<sup>b</sup>Flywheel, 68 (150); continuously variable transmission, 70 (154).

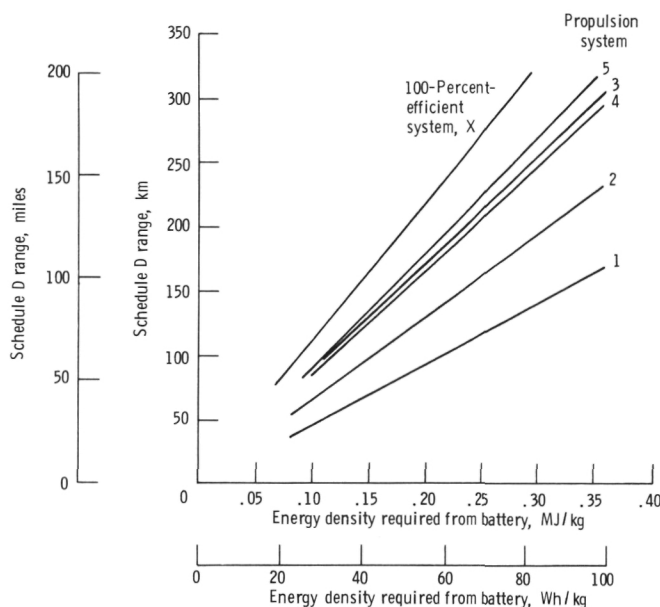


Figure 8. – Energy-range relationship for various propulsion systems.

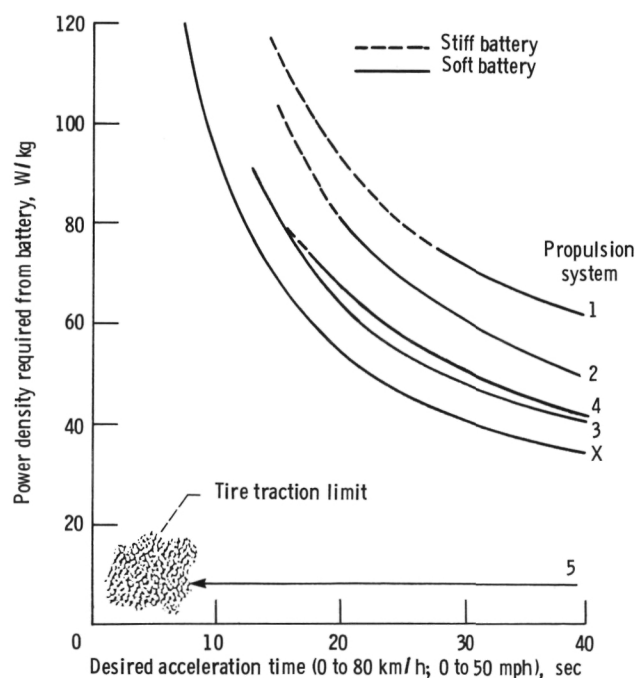


Figure 9. – Power-acceleration time relationship for various propulsion systems.

battery be able to provide the energy density for the amount of time necessary to cover the specified range at the Schedule D rate of about 48 km/h (30 mph). For example, to achieve a range of 145 km (90 miles) with propulsion system 4, a battery would have to provide an energy density of 50 Wh/kg (23 Wh/lb) for 3 hours. The effect of the shape of the voltage-current characteristics of the battery (i.e., stiff or soft) is about 2 percent. That is, for a particular system the range with the soft battery

is 2 percent less than the range with the stiff battery. This small difference indicates that the power-conditioning unit, which was designed for an unregulated voltage, functions efficiently for all of the systems. Values plotted are averages.

The absolute value of the range shown in figure 8 is not especially significant because it depends on the battery data, the battery model, and component models used in the simulation. The significance of the plot is that it shows that increases in vehicle range will be small beyond the technologies of systems 3, 4, and 5. For these systems the total energy consumption over Schedule D is only 15 to 30 percent greater than the energy consumption due to the road losses (table V). Consequently, to increase the range of an all-electric vehicle with a purpose-designed propulsion system, it is necessary to obtain more energy from the battery.

For the range calculation the strategy for system 5 was simply to use only the flywheel during the acceleration part of the Schedule D driving cycle and only the motor during the cruise part. The strategy also required that flywheel speed at the end of the D cycle be the same as at the start. During braking, regenerated energy was returned to the flywheel. During cruise the battery supplied energy to recharge the flywheel as well as to power the vehicle. Thus, the battery supplied all of the energy for the cycle, and the flywheel was recharged in part directly by the battery and, in part, indirectly by the battery through the regenerated energy.

Figure 9 shows how acceleration demands on the vehicle affect the power required from the battery. Note that the power density required from the battery must be available for the desired acceleration time. To generate these plots, we first calculated velocity-versus-time profiles for approximately constant power acceleration from zero to 80 km/h for acceleration times of 7, 10, 15, 20, 25, 30, and 40 sec. The velocity-time profile was put into the HEAVY program, which then calculated the power density that the battery must supply to meet the

TABLE V. – CALCULATED ENERGY CONSUMPTION FOR SCHEDULE D DRIVING CYCLE

Propulsion system	Energy consumption			Vehicle test weight	
	MJ/km	Wh/km	Wh/mile		
				kg	lb
1	0.96	268	429	1680	3704
2	.69	193	310	1796	3959
3	.53	147	236	1651	3640
4	.54	151	243	1562	3444
5	.48	134	219	1714	3779
X <sup>a</sup>	.42	118	190	1651	3640

<sup>a</sup>Because system X uses 100-percent-efficient components, the energy consumption represents the road losses due to drag and rolling resistance.

specified velocity-time profile. This calculation was done for both the stiff and the soft battery representations. In the figure the solid-line portion denotes the results using a soft battery, and the dashed-line portion gives the results using a stiff battery. Thus, systems 1, 2, and 4 are able to accelerate to 80 km/h in 15 sec with a stiff battery, but only in 28, 20, and 18 sec, respectively, with a soft battery. The difference in performance with the two battery representations is due to the voltage dropoff of the soft battery. For system 1 the drop in battery voltage reduces the torque available from the motor because of the characteristic variation of the series motor torque-speed curve with voltage. For systems 2 and 4 the decreased battery voltage results in the need for more battery current to meet the acceleration power requirements, but the controllers in the propulsion systems are current limited and thus limit power to the motor.

In system 3 the controller is bypassed at vehicle speeds above 34 to 42 km/h (21 to 26 mph). This reduces considerably the effect of the soft battery by allowing increased current to the motor up to the motor current limit.

System 5, of course, shows the best acceleration because it uses flywheel energy for acceleration. Energy available from the flywheel between full speed and half speed is 0.9 MJ (250 Wh).

## Propulsion System Components

Electric vehicle propulsion systems are made up of components: motors, controllers, transmissions, etc. As pointed out in the section on propulsion systems, the key component is the motor. The controller serves the power control needs of the motor, and the transmission matches the mechanical output of the motor to the vehicle

performance requirements. Components must be selected, matched, and designed to result in cost-effective and efficient propulsion systems.

This section presents a brief discussion of the various types of motors, controllers, transmissions, and energy storage devices. Their characteristics are compared generically and in a qualitative manner. The discussion is based primarily on the results of propulsion development efforts managed by the Lewis Research Center for the DOE E&HV program.

The rating, or ratings, of a propulsion system component for electric vehicle application cannot be specified explicitly at this time. As an analogy, consider the difference between a 100-kW automobile engine and 100-kW truck and bus engines. Each has been developed to satisfy its particular application. A way remains to be developed to consistently specify the design rated power of an electric vehicle propulsion system and its components. Therefore, in the DOE efforts the components were designed to meet the duty cycle shown in figure 10. The indicated cyclic power requirements are those needed at the motor output to drive a 1450-kg gross weight vehicle over the SAE J227a Schedule D driving cycle. One gear ratio change was allowed during the acceleration portion of the cycle if the propulsion design would benefit from it. Also specified was the capability to cruise at a constant speed of 88 km/h and to climb a 10-percent grade at 48 km/h. Cooling was to be by means of natural convection or forced air. Liquid or other cooling mediums were allowed if it could be shown that the overall vehicle would benefit. Components developed to provide this performance characterize the approach at a practical power level and should be scalable to other power levels as required. In the discussions in this report reference is frequently made to components developed as part of the DOE E&HV program. Except where indicated otherwise, these components were all designed for the performance shown in figure 10.

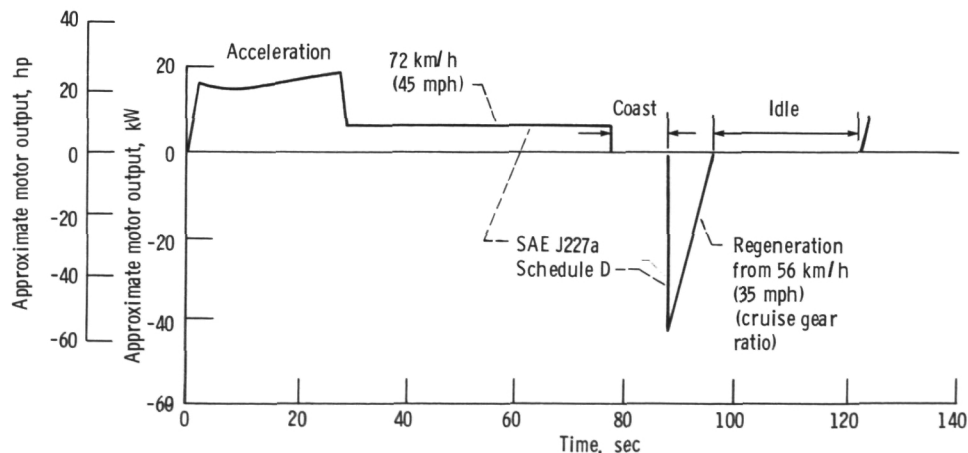


Figure 10. - Typical motor duty cycle for electric urban passenger vehicle.

## MOTORS

In this section the various motors that can be considered for electric vehicle propulsion, as shown in table I, are discussed.

Motors as electric machines can be separated into two broad classifications: (1) direct current (dc) types, and (2) alternating-current (ac) types. Motors classified as direct current operate from a dc source and contain, within their generally accepted package, the mechanical commutators and brushes needed for motor operation. Motors classified as alternating current operate from an ac source and, for the purposes of this report, do not contain a mechanical commutator within their package. There are commutator ac motors, such as those used in some ac electric railway systems. But these were not considered for electric vehicle propulsion because they offer no advantage over a dc motor system.

There are two general mechanical configurations into which rotating electric machines can be grouped. The first is the most common configuration, the "drum," in which the working air gap is a tube between a cylindrical rotor and stator. The air-gap thickness is in the radial direction. Unless otherwise stated, all discussion in this report is with reference to the drum configuration. The second mechanical configuration is the "disk," in which the working air gap is in the axial direction between disk-shaped rotor and stator sections on either side.

All rotating electric machines (motors and generators) can be generally thought of as torque machines. The torque developed in a drum-configured motor is proportional to the square of the machine's air-gap diameter times the air-gap length. The power produced is the product of the developed torque and the operating speed. This relationship is expressed in the well-known  $D^2L$  equation:

$$P = KD^2L\omega \quad (1)$$

where  $P$  is power,  $D$  is the average air-gap diameter,  $L$  is the air-gap length,  $\omega$  is rotational speed, and  $K$  is a constant determined by machine electromagnetic design.

The machine's volume and weight are related to the product  $D^2L$ , but many other design features enter into the total machine dimensions. These are type of machine (ac or dc), necessity for a commutator, cooling means, mechanical strength requirements, etc. However, from equation (1) it can be seen that, for a first approximation, a high-speed machine will be smaller than a slower machine for the same power. This relationship should be kept in mind through the discussions that follow.

The power-size equation for disk motors is not as well defined as that for the drum motor because of the greater number of variables in a disk motor. For instance the inner and outer radii of the active windings in a disk motor can be varied independently and various optimums exist. In general, as with drum motors, the power

produced by a disk motor is proportional to its volume and speed (for any particular design approach).

### Direct-Current Motors

The speed and torque of dc motors are generally easily controlled through some form of dc voltage or current control. Also, design concepts, rating methods, and manufacturing facilities for these motors are well established as a result of many years of industrial use. Because of this, electric vehicle propulsion systems have, almost exclusively, used some form of dc motor. But these are generally heavy and special-design, low-volume production motors. The variety in dc motors is extensive, and they can be grouped in several ways: (1) by excitation means—electromagnet or permanent magnet; (2) by air-gap orientation—radial (drum) or axial (disk, pancake); or (3) by winding configuration—series, shunt, or compound, etc. A convenient grouping for purposes of discussion is by excitation means (electromagnet or permanent magnet). This is indicated in table I. Electromagnetic excitation provides the main magnetic flux in the machine by means of a wound field and an external source of field power. Permanent magnet excitation provides flux by means of permanent magnets built into the machine. There are a number of special-purpose dc machines such as slipring homopolar types and brush-shifting types. These special types are not attractive for electric vehicle propulsion because of their relatively large size, greater weight, complexity, or higher cost and are not included in this discussion.

Direct-current motors are limited by the requirement for a commutator and brush network to supply armature power. The brushes wear and require periodic maintenance, and the limitation on peripheral speed of the commutator, in turn, limits the amount of size reduction, with speed increase, that can be accomplished to improve power density.

**Electromagnetically excited motors.**—Electromagnetically excited motors are, by far, the most common type in power ratings appropriate to electric vehicle propulsion (5 to 40 kW). There is an extensive body of design and manufacturing experience for these motors, and they can be optimized for almost any application. They can be totally enclosed and nonventilated, forced-air cooled, or liquid cooled, etc. Motors of designs suitable for electric vehicles generally are air cooled with either an integral shaft-mounted fan or a separate blower. These motors generally weigh of the order of 3 to 8 kg/rated kW (5 to 13 lb/hp). Existing designs probably represent the best compromise between cost, weight, efficiency, and durability. But certainly designs for high-quantity production motors for electric vehicles could reduce costs somewhat and tailor durability to vehicular use and expected life patterns. Presently available motors probably are much longer lived than would be required in

a private passenger vehicle. Representative weights and efficiencies that can be expected in electric-vehicle-sized motors are shown in table VI.

Electromagnetically excited motors are most commonly grouped by field winding connection. Grouped in that manner, dc motors are series, shunt, or compound. As figure 11 shows, there is little external physical difference between these groups. It should be pointed out here that the literature sometimes uses the term "separately excited" when describing a motor in which the excitation power for the field is provided by a controlled power source independent (or mostly so) of the armature power control. According to the IEEE Standard Dictionary of Electrical and Electronic Terms (IEEE STD 100-1977) (ref. 16), such a machine is a shunt-wound machine. All electromagnetically excited motors (series, shunt, or compound) are separately excited in that the source of excitation is external to the motor. In this discussion, therefore, "shunt" will be used to refer to motors in which the field windings are not in series with the armature.

**Series motors:** In series motors main-field magnetic flux is produced by field windings that are connected electrically in series with the motor armature as shown in figure 12(a). These windings consist of a few turns of large-cross-section conductors since full armature current flows in them. At low loads the torque produced by a series motor is proportional to the square of armature (and field) current. At heavier loads, where the iron in the motor becomes saturated, the torque is proportional to the armature (and field) current. These relationships are given in equations (2) and (3).

$$T = K_2 I_a^2 \quad (\text{at light load}) \quad (2)$$

$$T \sim K_1 I_a \quad (\text{at heavy load}) \quad (3)$$

TABLE VI. - WEIGHT AND EFFICIENCY OF DIRECT-CURRENT PROPULSION MOTORS

Motor	Weight		Efficiency at 11 kW <sup>a</sup> , percent
	kg	lb	
Series wound, GE 5BT2366C10, 23.8 kW rated	108	238	85.3
Series wound, Prestolite MTC-4001, unrated	45.5	100	77.5
Series wound, Northwest 250-100-0033A, 14.9 kW rated	85	187	89
Shunt wound, GE 5BY436A1, 14.9 kW rated (from ETV-1)	99.3	219	83.2
Shunt wound, Reliance EV-250AT, 13.4 kW rated	165.3	364	84
Shunt wound, Siemens 1GV1-161, 17 kW rated with 90-liter/sec minimum cooling air	89.8	198	85

<sup>a</sup>At best speed.

The constant  $K_1$  is commonly called the motor torque constant and is expressed as torque per ampere;  $T$  and  $I_a$  are average torque and armature current, respectively. The speed characteristic of a series motor is governed approximately by the equations

$$N = \frac{K_3}{I_a} \quad (\text{at light load}) \quad (4)$$

$$N = K_4(V - I_a R) \quad (\text{at heavy load}) \quad (5)$$

where  $N$  is motor speed,  $V$  is the average applied motor voltage,  $R$  is motor resistance; and  $K_2$ ,  $K_3$ , and  $K_4$  are constants that depend on motor design. Characteristic speed-torque and speed-current curves for a series motor are given in figure 12(b).

Series motors of a drum (radial air gap) configuration have been the most popular for electric vehicles, and they are almost universally used in electric golf carts and electric industrial trucks. This popularity is the result of their attractive torque characteristics at low to moderate speeds and their ease of control. Motor speed (and torque) is controlled by varying the applied average dc voltage. Because of their wide usage, series motors are more readily available, in ratings suitable for electric vehicles, than other dc motors.

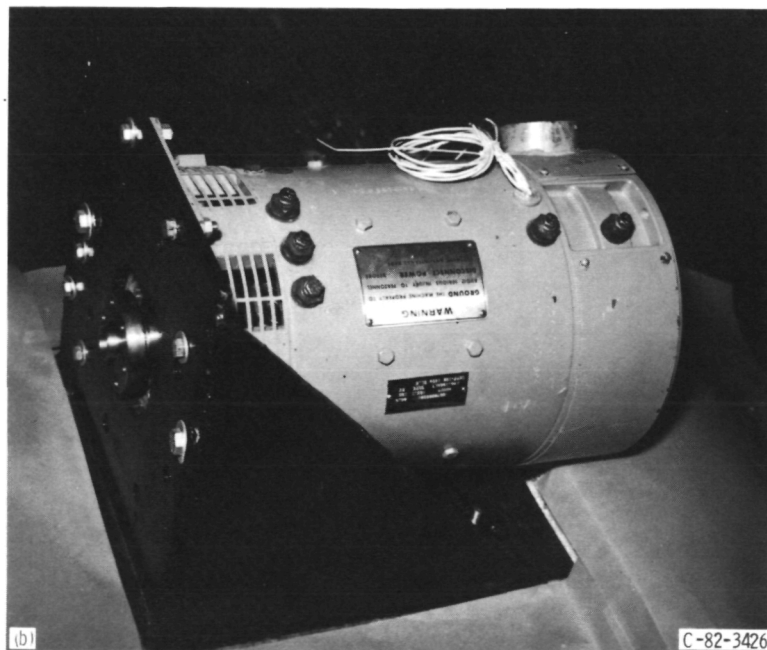
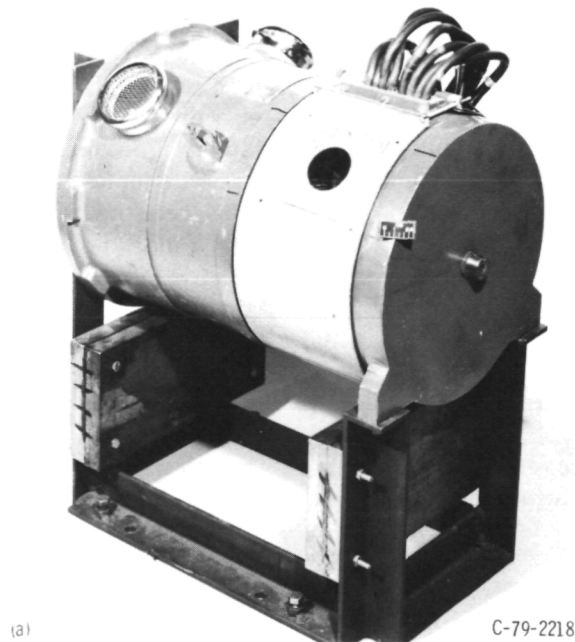
As part of the DOE E&HV program, several representative series motors were characterized under ripple-free and chopper armature voltage control (refs. 7 and 17 to 19). Additionally, under a university grant an in-depth study of the losses in chopper-controlled series motors was completed (ref. 20). The results of these efforts indicate that series motors controlled by chopper controllers generally have a lower efficiency than when operated from a ripple-free supply. This reduced efficiency exists over a significant portion of the motor's operating range as typified by the curves shown in figure 13. It is caused by the ac components of the motor current with chopper control and the resultant increased losses.

Series motors represent old, well-developed technology and little change in their design can be anticipated. The brush-commutator and rotor windings limit the maximum speed of practical motors for electric vehicle use to around 8000 rpm, although 5000 rpm appears to be an acceptable compromise between rotational-speed-induced problems (such as commutation and mechanical stress) and machine weight and cost. An inherent characteristic of a series motor, as indicated by equation (4), is its tendency to accelerate to very high, usually destructive speeds if unloaded without suitable control or safeguards. Therefore, these machines should not be used in systems where driveline breakage is probable, such as belt-driven systems or systems with clutches.

Series motors can be operated as generators for regenerative or dynamic braking, but control of the

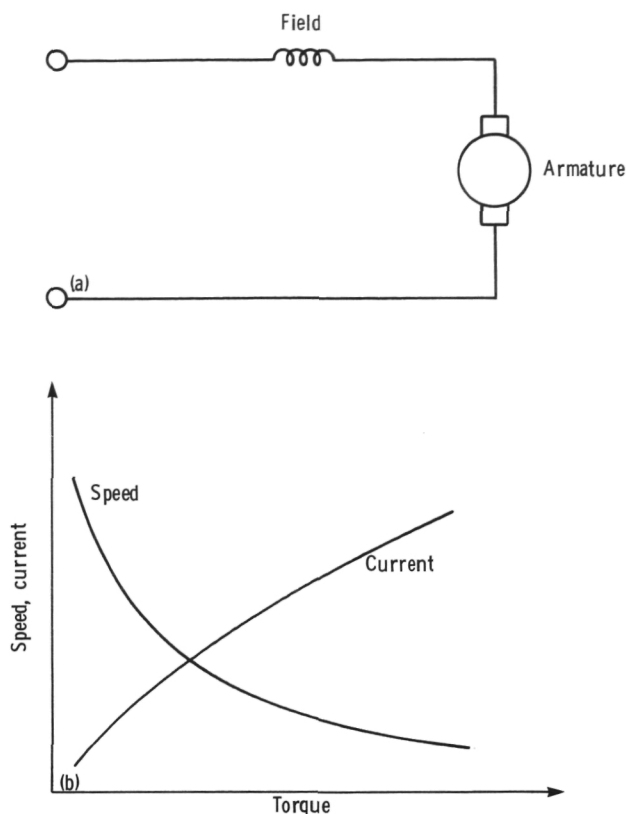
regeneration requires special provisions in the controller. These include a polarity-reversing main armature circuit contactor and voltage boost capability at low speed in the chopper controller. These control requirements make regeneration less attractive with series motors than with shunt motors. Regeneration is discussed further in this report in the sections on other motor types and controllers.

Series motors in a disk (axial air gap) configuration are possible but seldom, if ever, seen. Interconnection of the field poles in a disk machine, especially with the large conductors of the series field, is difficult and wasteful of materials. Also, the disk configuration makes less efficient use of electromagnetic parts (copper and iron) unless an ironless rotor is used. The large air gap presented by the ironless rotor with heavy windings



(a) Series wound. (b) Shunt wound.

Figure 11. - Typical dc motors.



(a) Field-armature connection.  
(b) Characteristic curves.  
Figure 12. - Series dc motor.

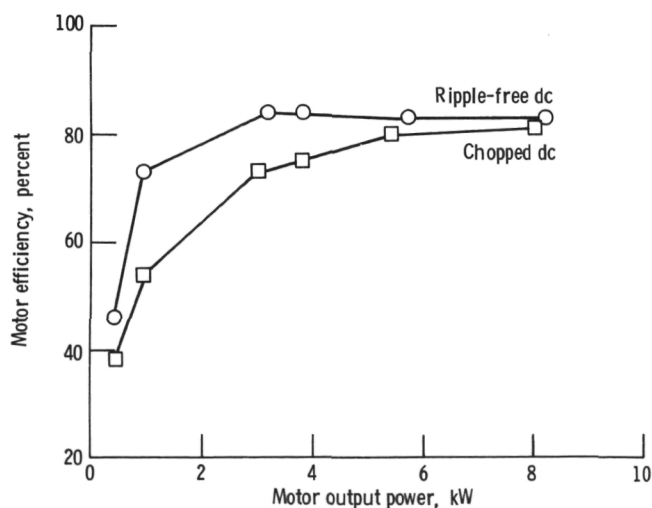


Figure 13. - Motor efficiency as a function of output power for 15-kW series motor. Rotational speed, 2000 rpm.

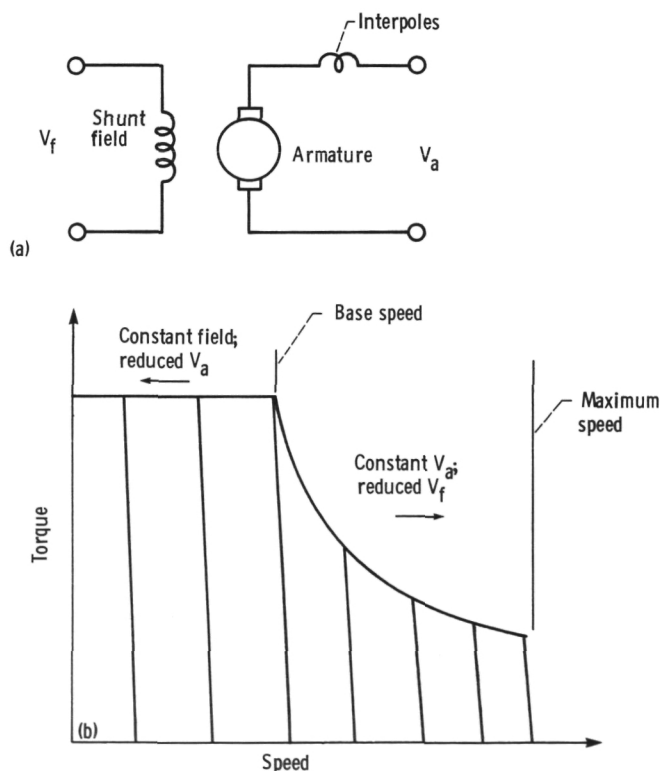
requires increased field excitation. Finally, a disk motor with iron in the rotor will have a relatively large inertia, which in many cases will limit its response to driver commands. The moment of inertia of a drum motor can be approximately one-fourth that of an equivalent disk motor with an iron-cored armature.

**Shunt motors:** Main magnetic field flux in a shunt motor is produced by field windings in which the current is, in general, independent of armature current as indicated in figure 14(a). Classically, these windings are connected in parallel (shunt) with the armature. In practice, power can be supplied to the field in a controlled manner from a variety of sources. The speed and torque of a shunt motor can be controlled by varying either armature or field voltage or by a combination of armature and field control. The general equations governing the speed and torque of a shunt motor are

$$T = K_5 \phi I_a \quad (6)$$

$$N = \frac{V - I_a R_a}{K_6 \phi} \quad (7)$$

where  $T$  is average torque,  $I_a$  is average armature current,  $\phi$  is effective field flux,  $R_a$  is armature circuit resistance,  $N$  is speed,  $V$  is average applied voltage, and  $K_5$  and  $K_6$  are constants determined by motor design. The magnitude of  $\phi$  is the result of all sources of excitation or demagnetization (i.e., main field, interpoles, compensating poles, and armature reaction). It is beyond the scope of this report to deal with the many facets of motor design and performance. These can be obtained from a good text on the subject.



(a) Field-armature connections.  
(b) Speed-torque characteristic.

Figure 14. - Shunt dc motors.

The power required to provide field flux in a shunt motor is a small percentage of the power at the armature input (approximately 5 percent of rated motor power). Therefore, as can be seen from equations (6) and (7), speed and torque can be controlled by varying the relatively low power in the field circuit. This can be accomplished with a variety of controllers ranging from rheostats to transistor-based switching controllers (choppers).

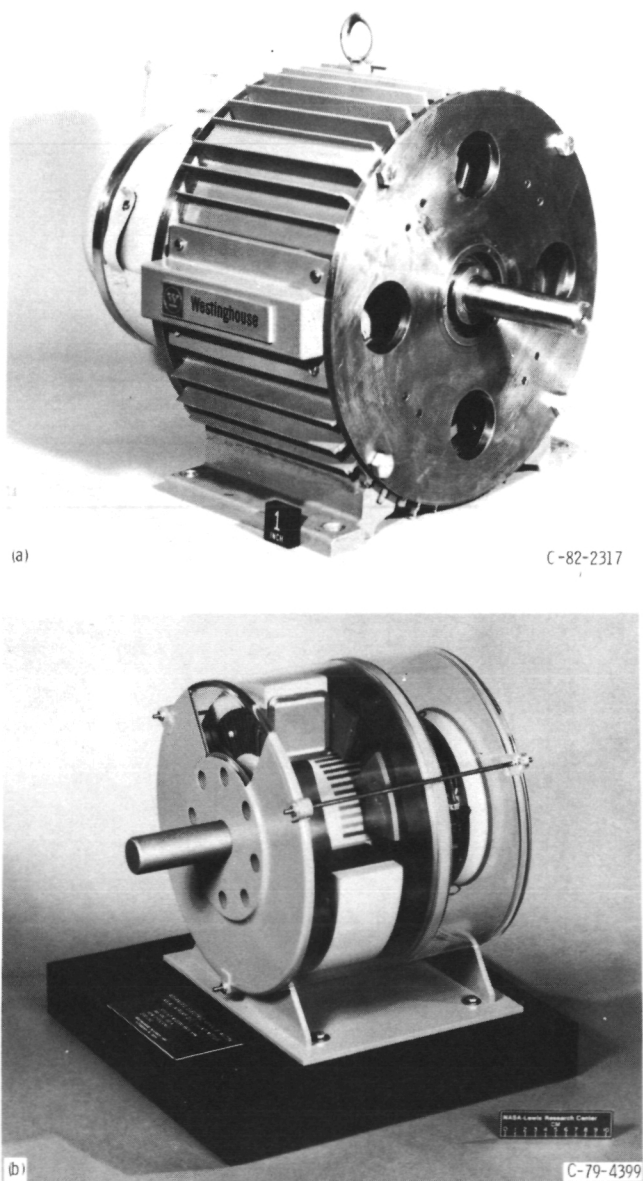
In discussing shunt motors the term "base speed" must be understood. Base speed is defined as the lowest stable speed obtained at rated load with rated voltages applied to armature and field. Operation at speeds below base is usually achieved by reducing the voltage applied to the armature. Increasing the field power to obtain speeds below base has limited effect because of magnetic circuit saturation and the potential for thermal damage to the field. Below base speed the torque can be held constant by decreasing the armature voltage in proportion to the speed reduction. The motor develops full power at base speed, with maximum efficiency. Above base speed the power that can be developed remains nearly constant. Field weakening is used to control speed, subject to the constraints of commutation limit, saturation limit, and thermal limit. Depending on motor design the maximum rated speed of a shunt motor may be from 1.5 to 3.0 times base speed. The interpoles and, sometimes, compensating windings needed to achieve this speed range add some cost and weight to the motor. Typical speed-torque curves for a shunt motor are shown in figure 14(b).

Use of a chopper to control armature voltage below base speed results in an efficiency penalty (as compared with ripple-free dc) similar to that described for series motors. Chopper control of field voltage above base speed has a negligible effect on motor efficiency because of the relatively low power in the field. Performance data for representative shunt motors are presented in references 21 and 22.

As with the series motor, shunt motors in a disk configuration are rare because of their fabrication, efficiency, and inertia drawbacks. The so-called printed-circuit motors have low inertia but are generally limited to power levels below those appropriate to electric vehicles. A possible exception to this is the Gramme ring disk motor, an old concept, but one with a potential for low cost. This concept for electric vehicles was investigated by the Westinghouse R&D Center (ref. 23). A full-rated engineering model motor of that design along with a cutaway model is shown in figure 15. This motor weighs 47 kg, or about 5 kg/rated kW (8.2 lb/hp). In concept, the armature could be wound at low cost on a toroid winding machine and commutation could be by means of brushes on inactive end-turns rather than through a separate commutator. Winding the armature with the required amount of copper has proven to be very

difficult. Windage loss, low efficiency, and inertia are unresolved problems. Therefore, further development of this concept for electric vehicles has been discontinued.

**Compound motors:** Compound-wound motors use both series and shunt main-field windings in varying combinations for specific purposes. The shunt field limits overspeeding and the series field provides good starting torque. The characteristics of a compound-wound motor depend on the balance between shunt and series fields. These motors are probably of little interest for electric vehicle propulsion because the polarity of both fields must be reversed for reverse rotation, and the series field must be reversed for proper regeneration. Control contactors to accomplish this would be cumbersome.



(a) Engineering model. (b) Cutaway model.  
Figure 15. — Westinghouse Gramme ring disk motor.

**Permanent magnet motors.** — Permanent magnet (PM) motors can be considered to be very similar to shunt-wound electromagnetically excited motors in which the field excitation level is fixed and provided by permanent magnets. Speed and torque in these motors are controlled by means of armature voltage control. Typical speed-torque lines for a PM motor are shown in figure 16. Since field power does not have to be supplied from an outside source, PM motors can be expected to be more efficient than equivalent electromagnetically excited motors. The relatively recent availability of rare earth-cobalt magnets has allowed reasonably sized PM motors to be designed in a power range compatible with electric vehicles. The rare earth magnets provide reasonable magnetic flux density and have a high resistance to the demagnetizing forces that occur under heavy, short-time loads. The older alnico magnets do not have such resistance, and the flux of ferrite magnets is too low to allow a reasonably sized PM motor for electric vehicles.

In electric vehicle propulsion the PM motor needs continuous armature voltage control. Also, it cannot be "deenergized." Under an internal fault condition the PM motor will supply current into the fault as long as the motor is rotating.

The rare earth magnets have allowed the design of PM motors that are noticeably smaller than electromagnetically excited motors in the power range of interest for electric vehicles. Size advantages of as much as one-half have been claimed by some manufacturers, but the cost and control limitations have prevented their use in electric vehicle propulsion. Since dc PM motors need commutators and therefore cannot fully take advantage of high-speed designs, they were not included in the DOE propulsion developments. It can be expected that these motors will continue to be developed for machine tool

and similar applications and that they may ultimately reach a stage where they will displace the electromagnetically excited motors in these and other applications.

Permanent magnet disk motors have seen noticeable development with the advent of better permanent magnets. The alnico and rare earth magnets have allowed the design of disk motors with ironless (printed circuit) armatures. These motors have been suggested for propulsion service and have been tried in several low-power applications (refs. 24 and 25). The ironless rotor has low inertia, but the need for a commutator remains. These motors need further development before their applicability to electric vehicles can be fully assessed. This development must include a full understanding of permanent magnet field distribution in a disk configuration. As part of the DOE E&HV program, an investigation into this subject was conducted at the University of Southern California. This research has provided information which indicates that magnetic field distribution in a disk motor depends on the magnet material used (ref. 26). The design of effective PM disk motors will benefit from this research. However, application of dc PM disk motors to electric vehicle propulsion does not appear to offer any compelling advantage over ac motors (discussed in the following section) at this time.

### Alternating-Current Motors

Although not often applied to vehicle propulsion, ac motors have been applied to other loads from watts to megawatts. An extensive body of theory and design practices has been built up over many years. In general, ac motors are much lower in cost than dc motors and provide long, trouble-free service. The advances in semiconductor power electronic technology in recent years have made polyphase ac motors a viable candidate for propulsion service. Rail mass transit is probably the most active field in ac propulsion development and use.

Single-phase ac motors are not attractive for vehicle propulsion because of their need for special starting circuits and low starting torque. Also, suitably rated single-phase motors are generally larger and heavier than equivalent polyphase motors. Three-phase ac motors have become the standard in industry because ac power transmission and utilization is optimized with three phases. In propulsion systems the optimum number of phases has yet to be defined. The ac propulsion developments managed by the Lewis Research Center as part of the DOE program have used three-phase machines because of their simplicity and the well-understood design options. However, investigative work under a grant with Cleveland State University on motors of higher phase order has also been pursued (refs. 27 and 28). Initial indications are that in inverter-driven systems,

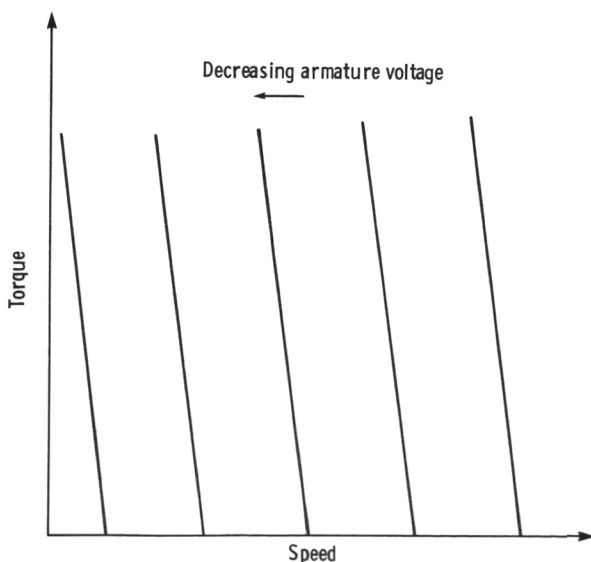


Figure 16. — Speed-torque characteristics of permanent magnet motors.

higher-phase-order motors may be slightly more efficient than three-phase motors. Higher-phase-order motors must be powered by inverters that are more complex than the three-phase inverters but that can use nonparalleled, lower-cost power semiconductors. The marginal increase in efficiency does not warrant extensive development of higher-phase-order systems.

Because they do not have commutators, the ac motors treated in this report can be designed for higher speeds than dc motors and therefore can be considerably smaller for the same power rating. Weights for air-cooled ac motors as low as 1.4 kg/rated kW (2.3 lb/hp), less than one-half that of a light dc motor, have been achieved in the E&HV Propulsion Development Project (ref. 29). Light weight implies less material and less material implies lower cost. Indeed, even today ac motors are less than one-half the cost of equivalent dc motors. It can be expected that, because of their simplicity, ac motors in mass production for electric vehicle propulsion will be even lower in relative cost.

The controllers needed to provide controllable speed and torque for vehicle propulsion with ac motors are more complex and larger than those needed for dc motors. The recent, and continuing, advances in semiconductor power electronics, components, circuits, and packaging will eventually result in ac propulsion systems of lower weight and cost than dc systems.

For the purposes of this report, ac motors are divided into two main groups based on the relationship of the rotational speed to the fundamental frequency of the alternating current that provides the main electrical power to the motor. These groups are induction (also called asynchronous) and synchronous. As these terms imply, the shaft rotational speed of the induction (asynchronous) motor is not in synchronism with the frequency of the electrical supply power, but that of the synchronous motor is.

**Induction motors.** — Induction motors are probably the most common form of electric motor. The operation of an induction motor, like other motors, can be explained by the interaction of two magnetic fields: armature (stator) and excitation (rotor). Where in other motors one field is generated by a means relatively independent of the armature, one of the fields in an induction motor is “induced” by the armature current through transformer action. With polyphase current flowing in the armature (which is usually on the stator) a rotating magnetic field is set up in the gap between stator and rotor. As this rotating field passes conductors on the rotor, current is induced in those conductors. The rotor conductors are connected in a winding, and the current in this winding, together with the rotor’s speed, produces a magnetic field that rotates in synchronism with the armature field. Torque is produced by the interaction of these two fields, and the currents in both windings are determined at least in part by the torque. If the rotor turned at the same

speed as the armature’s rotating magnetic field, no current would be induced in the rotor conductors, no rotor field generated, and no torque produced. For an induction machine to work as a motor, the rotor must turn at a speed less than the rotating field caused by the armature. The difference in these two speeds is the “slip.” Slip is commonly expressed as a percentage for constant-speed motors, but for variable-speed induction motor systems it is expressed in hertz (the difference in speeds as related to armature frequency). Slip for motor operation is termed “positive.” If the rotor is forced by an external source of mechanical energy (regeneration in electric vehicles) to turn faster than the rotating magnetic field produced by the armature (negative slip), the induction machine will function as a generator. The resistance of the rotor winding has a direct effect on the motor’s efficiency and speed-torque characteristic. A low-resistance winding results in an efficient motor with low slip and low stall (zero speed) torque as shown by the solid curve of figure 17. Slip at maximum torque will generally be less than 10 Hz. A high-resistance winding results in lower efficiency but higher stall torque as shown by the dashed curve of figure 17.

The control approach used for induction motor electric vehicle propulsion systems allows the use of low-resistance, high-efficiency rotors while still providing high stall torque. This control is accomplished with a variable-voltage, variable-frequency polyphase inverter supplying power to the induction motor. The curves shown in figure 18 are representative of the speed, torque, frequency, and voltage characteristics for an induction motor operated in a controlled manner from such an inverter. Motor speed is determined primarily by the frequency applied to the armature. Motor torque depends on the slip (more torque requires more slip). Induction motor propulsion systems increase slip up to

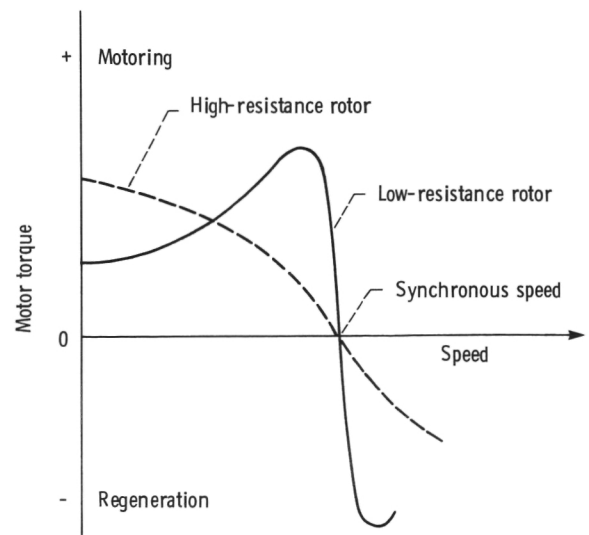


Figure 17. — Speed-torque characteristics of induction motors.

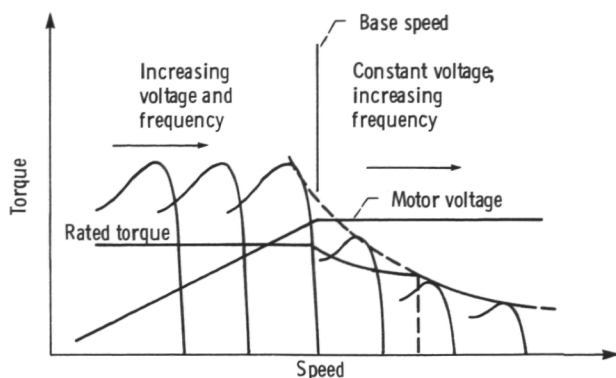


Figure 18. — Torque-speed characteristics of induction motors with variable-speed drive.

the motor's breakdown torque. Slip greater than this will result in a stalled motor or an inefficient and detrimental operating condition. For speeds from zero to some intermediate speed (base speed) the inverter increases both the frequency and voltage applied to the armature in a manner to obtain the desired speed and torque efficiently and without saturating the magnetic paths in the motor. In this range the system tends to be a constant maximum-torque producer. At the base speed, voltage is at the maximum available as determined by the supply (battery). For operation above the base speed, only frequency is increased. This results in lower magnetic flux levels in the machine and in the motor acting as an approximate maximum-power producer. For regeneration, similar control is used but with negative slip. Further details on the operation of induction machines in

electric vehicle propulsion systems are given in references 29 and 30.

Two general classes of induction motors can be considered for electric vehicle propulsion: squirrel cage and wound rotor. This distinction is based on the rotor configuration. The stator (armature) is essentially the same for both.

**Squirrel-cage motors:** Induction motors with squirrel-cage rotors are very nearly the simplest and most rugged type of electric motor. The stator is typically the same as, or very similar to, that of other ac motors — a polyphase winding distributed in a slotted, laminated iron core. The rotor is the distinguishing element of squirrel-cage motors. It generally consists of a laminated, slotted iron core with conductor bars in the slots. The conductor bars are all connected together at both ends by conducting rings. The bars and rings are the rotor winding and form a closed electrical circuit resembling a squirrel cage. The rotor and stator shown in figure 19 form the induction motor used by Gould in the development of a controller for an induction motor propulsion system. This motor can be considered representative of induction motors in the power range applicable to automotive vehicle propulsion.

Since the inverter in an induction motor propulsion system provides the motor with a frequency that is actively controlled to provide the required slip, the rotor winding can be made to have low resistance for high efficiency. In most induction motors the rotor winding is made of aluminum bars with integral end connecting rings, all cast into the stacked core laminations as shown in figure 19. As of this time, this method of rotor

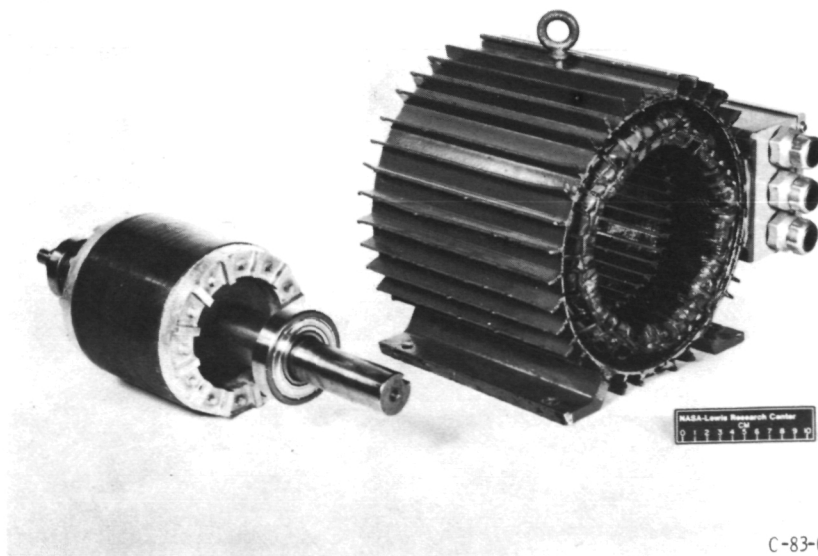


Figure 19. — Modified commercial squirrel-cage induction motor.

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construction is most economical and results in good performance when properly designed to work in an inverter-driven system. Higher efficiency can be obtained with a copper rotor winding as shown in figure 20. The motor of figure 20 was specifically designed (stator and rotor) by the General Electric Company for use in an inverter-driven system (ref. 29). This motor is shown along with an equivalently rated, but larger, dc shunt motor in figure 21. The maximum speed of the rotor in

the ac motor is 15 000 rpm, but an integral gearbox provides a maximum output shaft speed of 5000 rpm, the same as the shaft speed of the dc motor. This figure illustrates two of the prime advantages of squirrel-cage induction motors over dc motors – they are smaller and lighter. The dc motor weighs about 98 kg; the ac motor, including the integral gearing, weighs only about 46 kg.

With the armature windings on the stator, induction motors can be readily designed to use liquid cooling. An

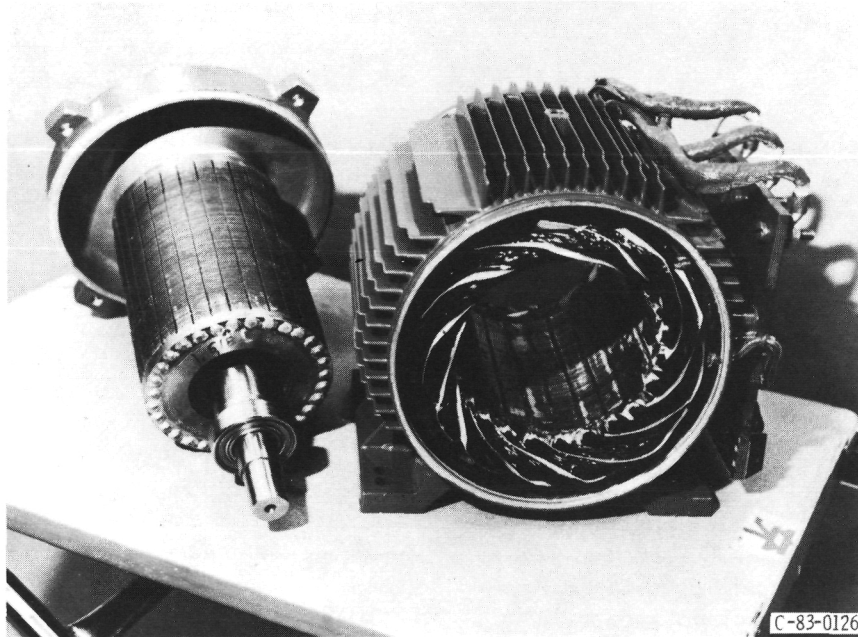


Figure 20. – Experimental squirrel-cage induction motor with copper rotor winding.

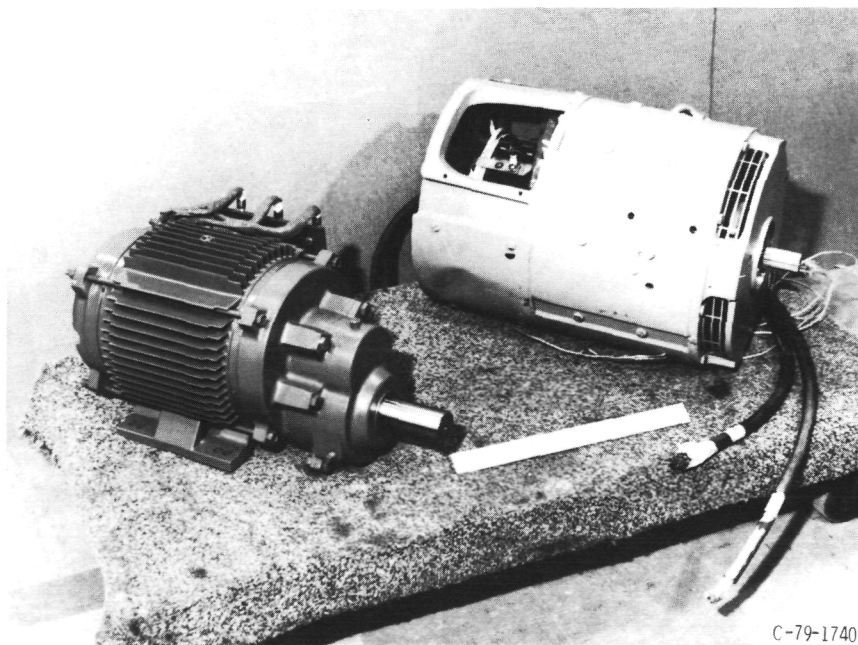


Figure 21. – Comparison of ac induction and dc brush-commutated motors.

oil-cooled induction motor that is part of a complete propulsion system being developed by Eaton's Research and Engineering Center is shown in figure 22. This motor has a maximum speed of 9000 rpm, but a later version operates at 12 500 rpm.

At this point in their development, designs of induction motors for vehicle propulsion systems are quite varied, resulting in a range of weights and speeds. Table VII contains representative information on squirrel-cage induction motors designed for, or adapted to, electric vehicle propulsion as part of the DOE E&HV program. From this table the obvious conclusion is that induction motor technology is fairly well established and that high-

speed motors are generally lightweight motors. In the final analysis, cost is the dominant factor. High-performance motors require more costly materials and manufacturing precision. Although they will be more costly than the lower performers, the life-cycle cost of the vehicle may be less. Induction motors are very amenable to mass production and therefore production quantity must also be considered.

*Wound-rotor motors:* As its name implies, the wound-rotor induction motor is an induction machine in which the rotor winding consists of insulated conductors wound on a slotted, laminated rotor core. In addition (and this is the primary reason for a wound-rotor configuration), the

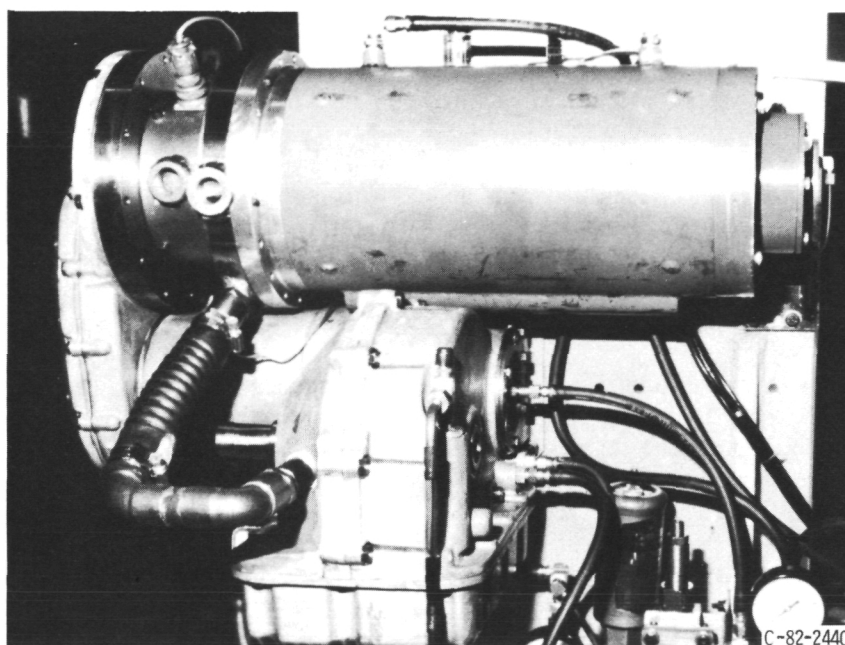


Figure 22. — Eaton oil-cooled induction motor.

TABLE VII. — PEAK POWER, WEIGHT, AND EFFICIENCY OF ALTERNATING-CURRENT INDUCTION MOTORS FOR PROPULSION

Motor	Peak power, kW	Weight		Efficiency at 11 kW <sup>a</sup> , percent
		kg	lb	
GE, special design, copper rotor cage, integral gearing, 15 000-rpm maximum rotor speed	≈ 40	<sup>b</sup> 46	101	<sup>b</sup> 89
Gould, modified industrial motor as load for inverter, 8000-rpm maximum rotor speed	26.1	53.2	117	80
Eaton, phase I, special design, oil cooled, aluminum rotor cage, 9000-rpm maximum rotor speed	29.8	67	148	90.6
Eaton, phase II, special design, oil cooled, aluminum rotor cage, 12 500-rpm maximum rotor speed	33.6	55	121	92

<sup>a</sup>At best speed.

<sup>b</sup>Including 3:1 stepdown gearing.

rotor circuit is made accessible via sliprings and brushes to control elements outside of the motor. With this accessibility to the rotor winding, these machines can be controlled in a number of ways. Rotor resistance can be varied while the machine is running, thereby varying its speed-torque characteristic on a fixed-voltage, fixed-frequency supply. By means of power electronic circuits, rotor power can be fed back to utility lines; this results in an efficient, variable-speed motor system.

The wound-rotor induction motor, however attractive for use on utility systems, has no advantage in electric vehicle propulsion systems. It has windings on the rotor, like a dc motor, which leads to greater complexity and cost as compared with squirrel-cage motors. It has brushes, which need maintenance. Like the squirrel-cage motor it must be supplied ac power by an inverter if it is to work in an electric vehicle. Control of a wound-rotor induction motor in an electric vehicle propulsion system would be more complex than control of a squirrel-cage motor because both stator and rotor circuits must be controlled. Finally, since all performance needs of an electric vehicle can be met with a squirrel-cage motor, there is little, if any, reason to consider the wound-rotor machine for that application. Wound-rotor induction motor development was not pursued in the DOE E&HV program.

**Synchronous motors.**—In synchronous motors the rotating part rotates at a speed that is in synchronism with the rotating magnetic field produced by currents in the polyphase armature winding. Three types of synchronous motors are treated in this report: (1) electromagnetically excited, (2) permanent magnet excited, and (3) unexcited, or reluctance motors. In the first two, motoring action can be explained by the interaction of two magnetic fields: the rotating field produced by the armature, and the excitation field. In usual practice the armature is on the stator of the synchronous motor and the excitation field is on the rotor. In operation the two fields can be considered locked together in an elastic manner. With the shaft rotating, the load torque causes the excitation field structure (rotor) to drop slightly behind its no-load position referenced to the armature-produced rotating field. The actual speed does not decrease. In motors used with constant-frequency systems too much load torque will cause the rotor to lag to such a degree that it falls out of step with the supply frequency and the motor stalls. The unexcited synchronous motor can be pictured as an unexcited rotor with magnetic saliency that stays lined up with the rotating armature-produced field. Since there is no excitation on the rotor, these unexcited motors tend to be larger than excited ones, but less costly. When driven by external shaft power, synchronous motors (except for the unexcited types) become synchronous generators. In electric vehicle propulsion systems synchronous motors

are not used as they would be in a utility, constant-frequency system. The inverter, which supplies ac to the armature, is controlled in a manner such that the rotor is always in synchronism even at very low speeds, down to zero. In effect, voltage is not applied to an armature phase until the rotor is in an angular position to develop the required torque. The inverter operates much like the brush-commutator set in dc motors. Because of this method of operation synchronous motors, together with their inverter and controller, as used in variable-speed drives (electric vehicle propulsion requires a very wide-range, demanding, variable-speed drive) are sometimes called "self synchronous" or "electronically commutated." In this report the electronically commutated (EC) terminology is used.

In the following sections, the synchronous machine part of the EC motor is discussed.

**Electromagnetically excited synchronous motors:** In these motors the excitation field is produced by solenoid windings on rotor saliencies commonly termed "poles." Current to excite these windings can be transferred to the rotor by several means. The most common is sliprings with brushes. Another is a rotating transformer with rectification on the rotor-mounted secondary. A third means is the use of an "exciter" alternator on the rotor shaft. This exciter is a small synchronous machine used as a generator. Its field on the stator is excited by a controllable dc source. Its polyphase armature is on the rotor and is connected via rectifiers to the main motor excitation field. With this third approach some control power is gained at the expense of motor complexity (and cost).

An electromagnetically excited EC motor could be designed for electric vehicle propulsion, and in operation it would be controlled in a manner similar to a dc shunt motor. Both excitation and armature voltage would be varied. However, the development of such a motor was not pursued as part of the Lewis-managed DOE E&HV Propulsion Development Project because it had limited advantage when compared with induction motors and permanent magnet (PM) EC motors. The PM EC motors are discussed in the following section of this report. Like a dc shunt motor the electromagnetically excited EC motor would have field losses plus armature control losses (in the inverter) as do other ac motors. Although offering more control flexibility, it is more complex than induction or PM synchronous motors. Its maximum speed would need to be limited to maintain integrity of the rotor windings. In short, it appears to have most of the disadvantages of a shunt motor plus the disadvantages of inverter-driven ac motors. Its speed limitation would limit its minimum size. Its only apparent advantage is the elimination of the need for a brush-commutator set.

**Permanent magnet synchronous motors:** The

permanent magnet (PM) synchronous motor is the basis for several very interesting EC motor developments that have been brought to the full-scale demonstration hardware stage as part of the Lewis-managed DOE E&HV Propulsion Development Project. These developments included both drum and disk motor configurations. Along with squirrel-cage induction motors, PM synchronous motors offer the potential of small, lightweight propulsion motors. Propulsion systems using either of these motors need similar forms of inverters, the present size and cost of which prohibit near-term commercial feasibility. As power electronics technology improves, propulsion systems based on either of these motors will become more attractive than present, or anticipated, dc motor systems.

Since the excitation for a PM synchronous motor is "built in," there are no field winding losses in the PM motor. In a comparison of equally constrained designs a PM motor will be more efficient than an induction motor. The PM motor can be controlled by the magnitude and timing of the voltage applied to the armature winding. The technology for such control has been developed in several successful forms as part of the E&HV Propulsion Development Project.

The various electric-vehicle-propulsion-related facets of PM synchronous motors cannot be adequately discussed without an understanding of how PM synchronous motors function as EC motors. Therefore a brief explanation of the EC concept is given next. Further, more detailed discussion on the power electronic aspects is given in the section on controllers.

The essential elements of an EC motor are shown in figure 23. The switching of the electronic switches in the inverter is controlled by gating circuitry based on signals from the shaft position sensor, which indicates the angular position of the excitation field. The combined operation of inverter, gating, and position sensor is analogous to brush commutation in conventional dc

motors. The converter (chopper) controls the voltage or current supplied to the motor and, in some designs, functions to allow proper operation of the inverter at low speeds.

Regeneration with PM EC motors is relatively straightforward. When the speed of the motor is high, the peaks of the voltage generated by the motor acting as a synchronous generator would be higher than the vehicle battery voltage, and regeneration is possible through the electronic commutation circuit. As the speed decreases, the generated voltage can be boosted by reconfiguring the chopper to act as a booster. These features are discussed in the section on controllers.

The relatively recent development and availability of high-energy, rare earth-cobalt (RECO) permanent magnets has spurred the development of PM motors for industry and aerospace. The successes in these fields have led to consideration of PM synchronous motors for electric vehicle propulsion. The cost and scarcity of materials for RECO magnets have been problems, but increasing production and new ore discoveries are expected to reduce these problems. Also, worldwide research efforts are resulting in high-energy permanent magnets with reduced dependency on samarium and cobalt. Permanent magnets are discussed further in the section on technology needs.

A cutaway model of a representative PM drum motor for electronic commutation is shown in figure 24. These motors are constructed so that the permanent magnet field is on the rotor and the armature is stationary. A number of important advantages result from having the armature winding stationary. The teeth and slots of the magnetic steel laminations become larger than in the rotating armature construction used in dc motors. The teeth can carry more magnetic flux and the slots can carry more copper. The net effect is that the resistance of the winding can be decreased, thus improving the efficiency. At the same time, the heat dissipation area of the winding

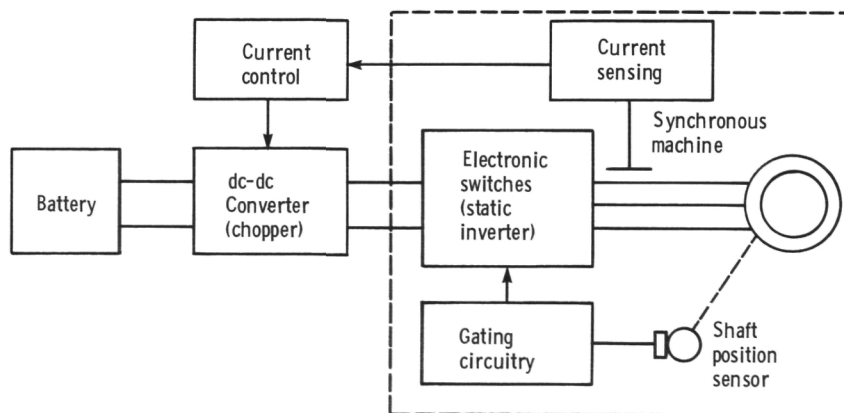


Figure 23. - Schematic diagram of electronically commutated dc motor.

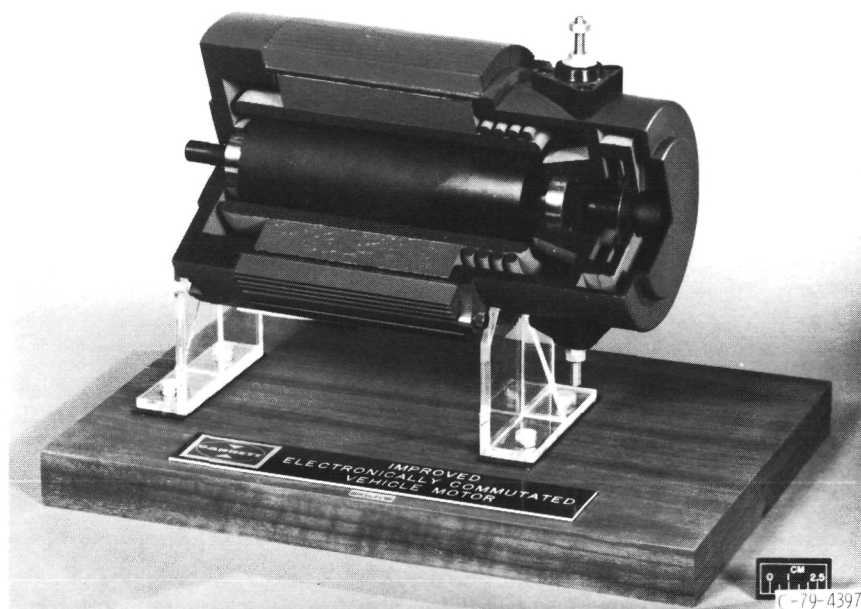


Figure 24. – Cutaway model of AiResearch permanent magnet, synchronous drum motor.

is increased. The negligible losses in the permanent magnet rotor eliminate the need for specific rotor cooling provisions. Sliprings and brushes are not needed. These features lead to a generally higher power rating than in a dc motor for a given temperature rise and machine size.

As part of the DOE E&HV program, AiResearch Manufacturing Company and Virginia Polytechnic Institute (VPI) were contracted to develop electronically commutated PM drum motors. Inland Motor was a subcontractor to VPI. Both contractors designed, built, and tested motors with samarium-cobalt ( $\text{SmCo}_5$ ) permanent magnets. To provide real hardware comparative data, VPI/Inland also designed, built, and tested a motor that used low-cost, but low-energy, ferrite magnets.

The two contractors took different approaches in achieving the goals. The AiResearch approach was a small, forced-air-cooled, high-speed motor. The 26 000-rpm speed of the motor, as high as can be tolerated by grease-packed bearings, resulted in its very low, 16-kg (35-lb) weight. It has been estimated that gearing to provide shaft speeds compatible with present automotive technology and mounted in a housing integral with the motor would result in a weight increase of about 2 to 4 kg (4 to 8 lb). Figure 25 shows the AiResearch motor. The tested efficiency of this motor, including the electronic commutation, is typified by the curves of figure 26. These curves indicate a peak efficiency of about 90 percent at full speed and fairly constant efficiency over most of the torque range. This efficiency includes electronic losses and is comparable to that of the best dc electric vehicle motors. In comparing

the electronically commutated PM motors with other approaches, it must be kept in mind that the commutation and control electronics contain virtually all of the control functions likely to be required for motor operation in an electric vehicle. Also, as a comparison, present commercially available dc motors in the power range of interest weigh from 60 to 90 kg (132 to 198 lb) without control electronics.

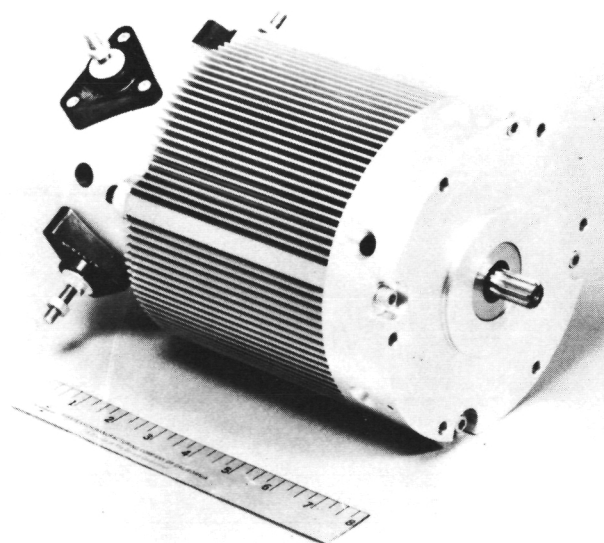


Figure 25. – AiResearch high-speed (26 000 rpm) permanent magnet, synchronous drum motor.

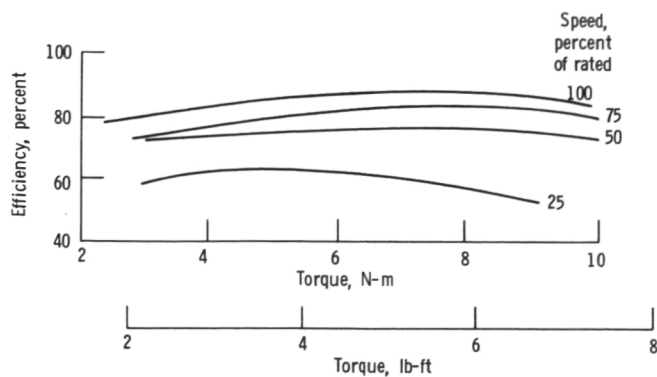
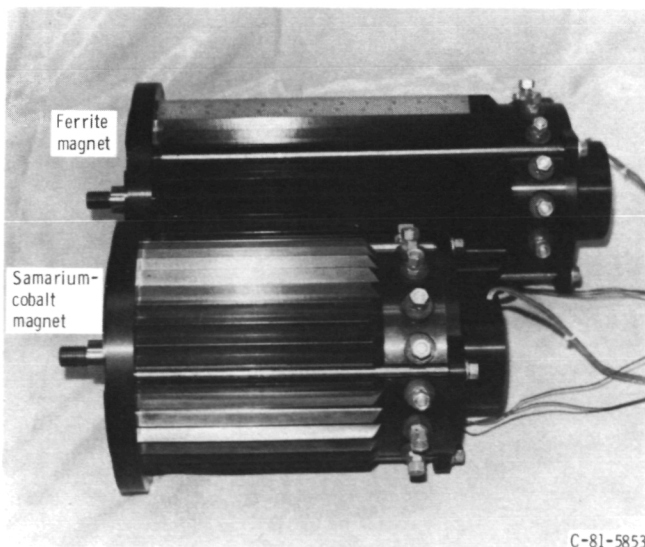


Figure 26. – Performance of AiResearch high-speed (26 000 rpm) permanent magnet, synchronous drum motor.

VPI together with its subcontractor, Inland Motor, used a medium-speed (8700 rpm), larger, convection-cooled design approach for both the samarium-cobalt and ferrite motors. These two motors are shown in figure 27. The smaller, samarium-cobalt motor weighs approximately 27 kg (59 lb); the larger, ferrite motor weighs approximately 58 kg (128 lb). These motors have their windings brought out to terminals to allow selection of a series or parallel winding connection externally. This will result in reduced motor current at low speeds if an automatic winding reconfiguration is used. VPI has tested the engineering models of their motors and has measured maximum combined motor-controller efficiencies of approximately 88 percent. The efficiency characteristics of the VPI/Inland EC motor are comparable to those of the AiResearch motor. It must be kept in mind that the existing hardware is in the



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Figure 27. – VPI/Inland Motors permanent magnet, synchronous drum motors.

engineering model stage and further improvement can be expected. Further details on these motors are given in references 31 to 33.

Although the maximum speed of the VPI/Inland motor is less than half that of the AiResearch motor, it is not quite twice as heavy. These are early designs done by independent designers, who probably used different design procedures. The VPI/Inland approach used finite element analysis to optimize the electromagnetic design of their machines. Also, as a motor design grows larger for a given power because of lower speed, the area available for heat removal increases, thereby reducing the size growth. These considerations must be kept in mind if any attempt is made to use equation (1) for scaling over a broad range of speed, power, or design constraints.

The developments completed have demonstrated the technical feasibility and benefits of this type of motor, and the continuing worldwide research in permanent magnets, along with the declining cost of power electronics, will enhance its commercial appeal. Which of these PM synchronous drum motors will have the best ultimate cost advantage is not clear at this time. The smaller high-speed types require more careful design and manufacturing procedures than the larger, slower motors but use less material. An optimized motor of the AiResearch design would weigh about 9 kg (20 lb) and use 0.67 kg (1.5 lb) of RECO magnets. It also would need forced-air cooling to operate within a safe temperature limit. There will be a small weight and efficiency penalty associated with this forced-air cooling system. The larger 27-kg VPI/Inland RECO motor needs no forced cooling but uses approximately 1.5 kg (3.3 lb) of RECO magnets along with more copper, iron, and aluminum. The still larger 58-kg VPI/Inland ferrite motor uses approximately 4.4 kg (9.7 lb) of low-cost ferrite magnets and still more copper, iron, and aluminum. But the reduction gearing needed for the larger, lower speed motors is simpler, less costly, and probably more efficient than that needed for the high-speed designs. Therefore the selection of an optimum motor design must be based on many constraints such as system efficiency, production volume, expected time frame for volume production (e.g., what is best today may not be best 10 yr from now), and so on.

In addition to the familiar drum configuration, permanent magnet synchronous motors for electronically commutated drives can also be made in a variety of disk configurations. Two such motors were investigated as part of the E&HV Propulsion Development Project. Unlike the drum motors, these two developmental disk motors are significantly different from each other. A cutaway model of the disk motor concept of the AiResearch Manufacturing Company is shown in figure 28. It is a homopolar design in which the rotor consists of a single central donut-shaped samarium-cobalt permanent magnet and two multifingered pole pieces. An

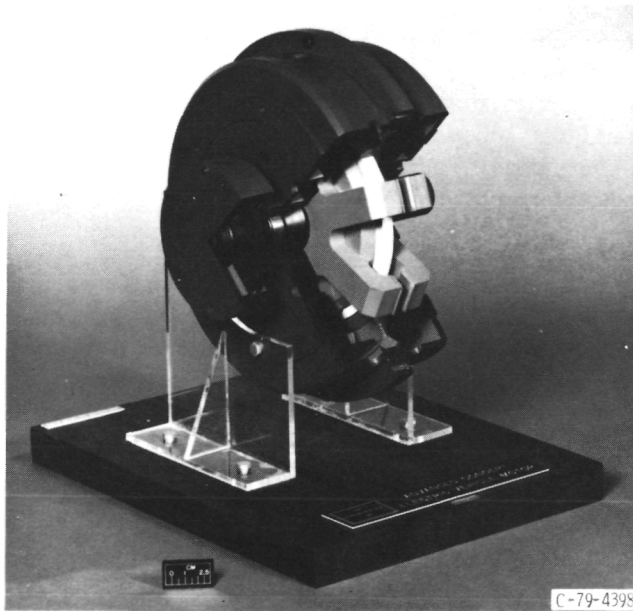


Figure 28. – Cutaway model of AiResearch permanent magnet, synchronous disk motor.

ironless stationary armature is located between the tips of the pole pieces. The maximum design speed of this motor is 14 000 rpm, and it is intended to be self-cooled by the air pumping action of the rotor. The housing is aluminum and serves no electromagnetic function. The electronic commutation for this motor will be similar to that for the drum motors. The first functional model weighed about 24 kg and demonstrated mechanical integrity and electromagnetic feasibility, but windage and eddy current losses were excessive. In the revised model, the rotor of which is shown in figure 29, interpolar space was filled and losses substantially reduced. The total

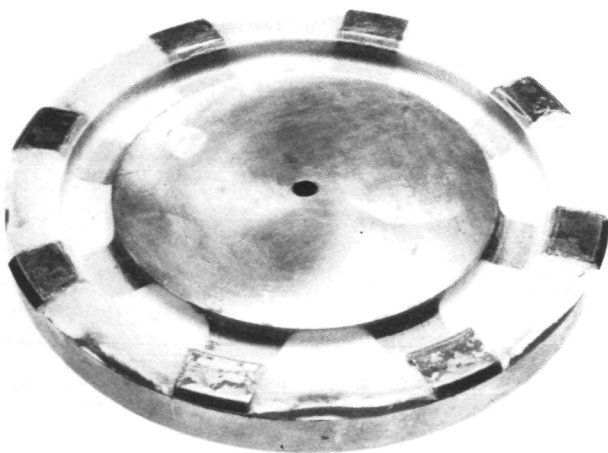


Figure 29. – Rotor pole piece for reduced-loss AiResearch disk motor.

losses were still somewhat high and resulted in a peak machine efficiency in the generating mode of about 85 percent at maximum speed and 90 percent at low speed and light load. These efficiency values are lower than expected, and when combined with controller efficiency will result in little, if any, improvement over today's technology. The simplicity of this motor, however, promises very low cost.

The General Electric disk motor concept uses multiple permanent magnets in an aluminum rotor. Stationary armature windings are located axially on each side of the rotor. An early version of this motor with the essential elements is shown as a cutaway in figure 30. A new permanent magnet material, manganese-aluminum-cobalt (MnAlC), was intended to be used in this motor. However, this material was not available in sufficient quantity to build the functional model. Therefore that model was made with substitute alnico magnets. Design maximum speed was 15 000 rpm. Mechanical integrity and functional performance were demonstrated, but the magnet strength deteriorated during testing as a result of high current pulses from the controller. Also, in a subsequent study by the University of Dayton (ref. 34), it was found that the originally intended MnAlC magnets would exhibit degraded performance at temperatures above 100° to 150° C and therefore are undesirable for use in vehicle propulsion motors. The functional model was therefore redesigned to use samarium-cobalt magnets and was built and tested. This redesigned motor, which weighed about 59 kg, is shown in figure 31 with one stator removed. Test results indicate peak combined motor-controller efficiencies approaching an excellent 92

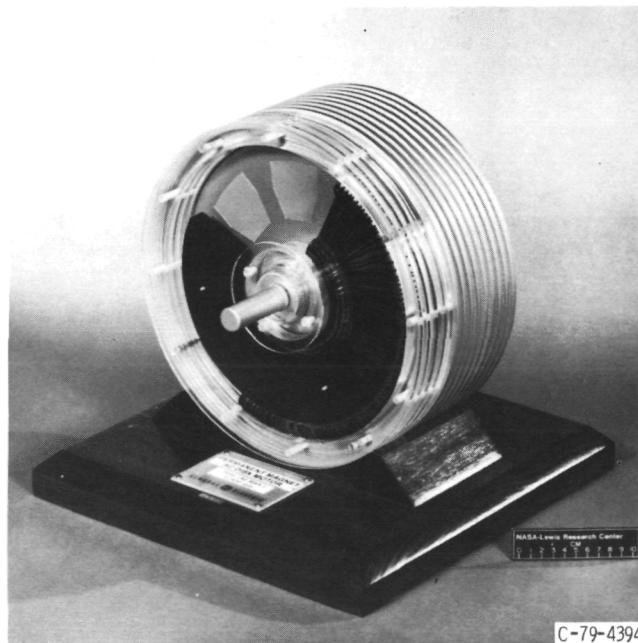


Figure 30. – GE permanent magnet, synchronous disk motor.

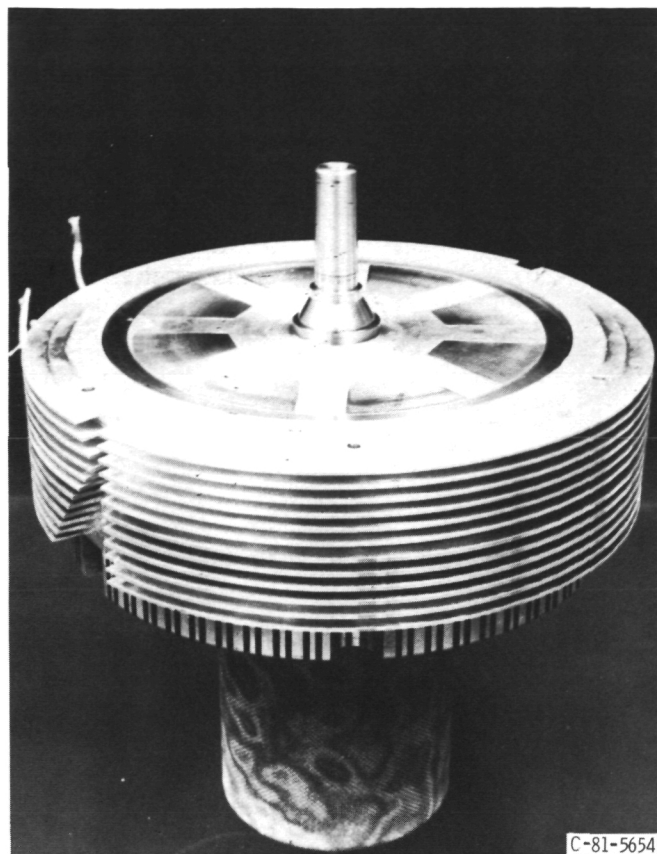


Figure 31. – Functional model of GE permanent magnet, synchronous disk motor.

percent and generally high efficiency over a broad operating range. Although the GE motor is more efficient than the AiResearch motor, it is also more complex, having multiple magnets and two armature windings. Detailed information on these two motor developments is given in references 35 and 36.

From the results of the development efforts on the

AiResearch and General Electric PM synchronous disk motors, several general conclusions can be reached: (1) the disk configuration has higher windage losses than the drum configuration; (2) the weight and efficiency of disk motors offer little or no advantage over the drum motors; (3) the disk rotor has higher inertia than the drum rotor, which could penalize vehicle performance; and (4) if suitable fabrication techniques and design modifications can be developed, disk motors may offer the potential of lower cost than drum motors because of simplicity. Overall, disk PM synchronous motors appear to have no compelling advantage over drum PM synchronous motors in electronically commutated propulsion systems for electric vehicles. The main design features, weights, and performance of the drum and disk PM synchronous motors developed in the E&HV Propulsion Development Project are summarized in table VIII.

*Unexcited synchronous motors:* There are two basic types of unexcited synchronous motors: reluctance and hysteresis. The hysteresis motor is widely used in clocks, timers, and other low-power applications because of its very low cost. It tends to be inefficient and heavy for its power and would be inappropriate for electric vehicle propulsion.

The reluctance motor (sometimes called variable reluctance) is widely used as a low-power, digitally controlled incremental-motion actuator. It is well suited for these applications because it is reliable and inexpensive and has a high power output per unit mass and a high starting torque per unit mass. The reluctance motor typically consists of a toothed rotor that rotates within a stator having three or more salient teeth or poles. The stator and rotor are made of soft magnetic material (laminated iron), and the teeth are designed so that the rotor aligns with the poles in sequence as the rotor turns. As a consequence of this toothed structure, the stator-rotor air gap exhibits a magnetic reluctance that varies with rotor position. As current is passed through the

TABLE VIII. – DEVELOPMENTAL SYNCHRONOUS PERMANENT MAGNET MOTORS

Contractor	Construction and magnet	Maximum rotor speed, rpm	Test machine weight <sup>a</sup>		Test machine efficiency at 11 kW <sup>b</sup> , percent
			kg	lb	
AiResearch	PM drum, SmCo <sup>c</sup>	26 000	15.9	35	<sup>d</sup> 84 <sup>e</sup> 87
VPI/Inland	PM drum, SmCo	8 700	27.2	60	<sup>d</sup> 87
VPI/Inland	PM drum, ferrite	8 800	57.6	127	<sup>d</sup> 84
AiResearch	PM disk, SmCo	14 000	23.5	52	<sup>e</sup> 80
GE	PM disk, SmCo	11 000	59	130	<sup>d</sup> 91 <sup>e</sup> 93

<sup>a</sup>Without electronics.

<sup>b</sup>At best speed.

<sup>c</sup>Requires external fan, approximately 2.7 kg additional.

<sup>d</sup>Motor and electronics together.

<sup>e</sup>Motor only.

windings wound around the stator poles, the position-dependent air-gap reluctances create a reluctance torque between the rotor and the stator that tends to align the rotor teeth with those of the excited poles. Thus, if the current in the individual pole windings is sequential, the rotor will turn so as to follow that sequence in synchronism. One such motor with eight stator poles, each with one tooth, and six rotor teeth is shown in figure 32. The repeated excitation sequence of windings AA', BB', CC', and DD' will produce a counterclockwise rotor rotation. The current in the stator windings would be controlled and sequenced by power electronic circuits. These circuits would be simpler than those needed for other ac motors because the reluctance motor does not require bidirectional stator current. There can be many variations of reluctance motors, and that shown in figure 32 is only an example.

As evident from figure 32 and the preceding brief discussion, the reluctance motor should be a low-cost propulsion motor for electric vehicles if it and its controls are adequately developed. Proprietary development of reluctance motor vehicle propulsion has been under way for some years in the United Kingdom (ref. 37). As part of the DOE E&HV program, an investigation of reluctance motors for application to electric vehicle propulsion has been started under a university grant to the Massachusetts Institute of Technology (MIT). Initial results indicate that a reluctance motor-controller can be designed to provide performance and weight comparable to those of induction motor systems but with simpler hardware. The simpler hardware should lead to high reliability and low cost. Much development is needed, though, before the true merits of a reluctance motor

propulsion system can be demonstrated with full-scale hardware.

There is no reason a disk type of reluctance motor could not be made. But there does not appear to be any advantage to the disk configuration at this time.

### Motor Technology Improvements

During the course of propulsion system development in the DOE E&HV program, technology for motors of low weight and high efficiency has been developed and demonstrated. The technology necessary to design and build very efficient motors has been available for many years, but the dominant concern has been cost. The recent advances in computer-aided design have allowed optimization of motor designs for specific applications such as the DOE electric test vehicle (ETV-1). The application of newly emerging power electronics technology together with computer-aided design has allowed the investigation and development of motors not normally considered for electric vehicle propulsion. High-speed ac motors, for instance, can now be designed to provide the required performance at high efficiency and with low motor weight. The simplicity of these motors together with their low weight, offers the promise of low cost. The motor developments of the E&HV program attest to this promise. As a class, induction motors will be less costly than equally constrained PM synchronous motors, but the PM motors will be more efficient because excitation power need not be supplied. An overall summary of electric vehicle motor progress since 1976 is shown in table IX. Further improvements beyond those shown in this table can be expected as development progresses.

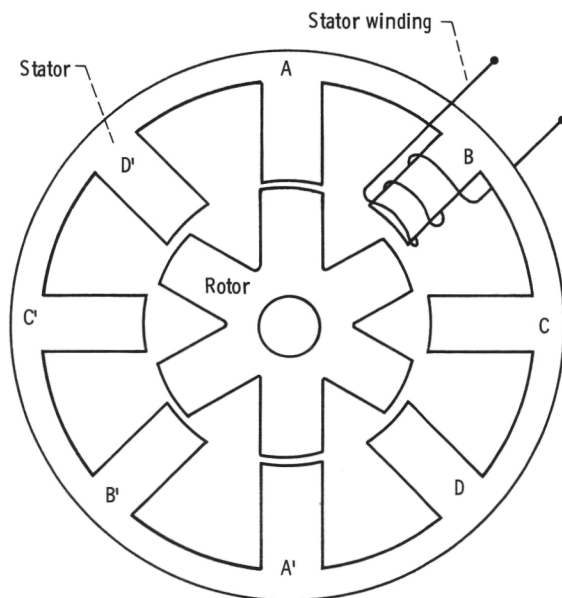


Figure 32. — Cross section of a reluctance motor. (Only one stator winding shown.)

### CONTROLLERS

In the field of electric vehicles, the term "controller" has various meanings depending on the background of the various individuals referring to it. To some it means all of the equipment needed to control the operation of the drive motor: power-handling components, power electronics (such as choppers and inverters), and the logic and sensors to control them. To others it means only the logic and low-power-level items that control the overall motor drive system. For the purposes of this report, controller refers to all of the power electronic equipment and to the logic and sensors needed to provide power to a motor so that the motor will deliver or regenerate propulsion power in a controlled, stable manner. Auxiliary items such as battery connectors, cabling, and circuit breakers are not included except where they perform an active role in the propulsion system control. A circuit breaker that serves to reconfigure a power electronic circuit for dual purposes would be part of a controller.

TABLE IX. – PROGRESS IN ELECTRIC  
VEHICLE PROPULSION

	At rated, steady-state conditions		
	Efficiency, percent	Specific weight, kg/kW	Specific cost, \$/kW
Motors (without control)			
Pre-1976:			
dc	80-90	4-8.5	75-150
ac <sup>a</sup>	85-90	2-3	16-30
Present development:			
dc	80-90	3-6	75-150
ac	88-93	2-3	(c)
Electronically commutated permanent magnet	90-95	1-2	(c)
Controllers			
Pre-1976:			
dc	85-95	0.5-2	40-50
ac <sup>a</sup>	87-92	4-6	250
Present development:			
dc	90-95	0.5-1.5	(c)
ac	90-95	2-3	(c)
Electronically commutated <sup>b</sup>	90-95	<sup>b</sup> 2-3	(c)
Transmissions			
Pre-1976:			
Manual <sup>d</sup>	94-98	1-2	20-25
Automatic <sup>d</sup>	75-85	1.5-2	25-35
Present development – automatic two-ratio transaxle	90-95	1.5-2	(c)
Systems			
Pre-1976 (dc)	45-60	10-15	120-300
Present development (ac)	65-80	5-7	(c)

<sup>a</sup>Not commercially available but early technology was. Data are estimates of values if items were available.

<sup>b</sup>Package development not complete, circuits nearly the same as those for ac controller. Package for electronic commutation estimated to be same as ac controller.

<sup>c</sup>Cost for newly developed technology not determined; detailed specific designs needed. Simplicity and low weight generally lead to low cost, and new technology is aimed at production simplicity and lower weight.

<sup>d</sup>Including torque-converter automotive transmissions used at electric vehicle power levels.

As in the case of motors, controllers can be divided for discussion into several classes. For this report the two major classifications are (1) dc motor controllers and (2) ac motor controllers, corresponding to the classification used in the section Motors.

### Direct-Current Motor Controllers

The techniques for controlling the speed and torque produced by dc motors are well documented in texts and other technical literature. The most practical means of controlling electric vehicle dc propulsion motors is by control of applied armature voltage or field excitation (field current). The series motor is normally controlled by

armature voltage control only, but field weakening can be accomplished with field bypass circuits. A shunt or compound-wound motor can be controlled by some combination of armature voltage and field current controls. In most electric vehicle propulsion systems the speed of the motor must be controlled from zero to its maximum value. This requirement leads to the use of both armature and field control of shunt or compound motors. If means other than motor speed are employed to accommodate zero and very low vehicle speeds (e.g., clutch and transmission), adequate control might be achieved with field control only.

The product of armature current and voltage is nearly the total electric input power to the motor (field power in a shunt motor is additional). Therefore armature voltage control requires the controller to handle full motor current. Field current, on the other hand, only provides motor excitation power that is of the order of 3 to 6 percent of the total motor power. Therefore field control provides a power "gain" in that the total motor output power can be controlled by controlling the low-power field.

Voltages supplied to a motor can be controlled in several ways: battery switching, rheostats, motor-generator sets, and switched-mode power electronics (choppers). Each of these are discussed in the following subsections.

**Battery switching.** – Battery-switching controllers can be the most efficient form of control of armature voltage, but they do not provide smooth operation. By means of switches, various voltages are fed to the motor. The switches can function to tap the battery string at various voltage levels or, by using all battery modules, to reconfigure the battery modules into various series-parallel connections to provide different voltages. In either case voltage control is in incremental steps. Smoothness of control depends on the number of voltage increments available. Two- or three-step controls are simple and low cost but may not provide acceptable control for an electric vehicle. As more steps are provided, the switching and cable matrix becomes more complex and the cost advantage over other control means such as a chopper is greatly diminished or disappears.

The switching action can be accomplished by relays or various proprietary drum or disk switches. In either approach the switching contacts and contact opening/closing must be designed to handle the large currents at relatively high voltage needed for adequate power in an electric vehicle. Currents to several hundred amperes at voltages at and above 100 V can be expected since battery switching is normally used for armature voltage control. Battery switching for field control is more easily accomplished because of the lower power level. However, switches in field circuit control are somewhat risky because a failure causing an open field circuit will tend to result in motor runaway or very large armature current.

Little, if any, advance in battery switching control can be expected beyond what is presently used or available. Therefore development of these controls was not a part of the E&HV Propulsion Development Project.

**Rheostats.**—A rheostat is basically a variable resistance. It is probably the oldest and, up to now, the most common means of control for dc motors, especially for starting from standstill. Rheostatic motor control consists of placing a variable resistance in series with the motor armature or field. Thereby the total circuit resistance (motor and rheostat) seen by the voltage source (battery) can be varied and motor currents smoothly controlled.

Rheostatic control can be very low cost, but it is obviously lossy and inefficient. In the armature circuit, where current can be in the hundreds of amperes and the voltage drop across the rheostat anywhere from zero to near battery voltage, the loss can be in kilowatts. If a rheostat is used to control field current for a shunt motor, losses can be considerably lower (as a percentage of total motor power) and may be acceptable for a low-cost, less-than-best-efficiency system. However, power electronic switch-mode (chopper) controllers in the power levels needed for field control in electric vehicle shunt motors can be made from relatively low-cost components. These chopper controllers can contain the control intelligence necessary for overall motor control and system protection and therefore, on a total propulsion system comparison basis, could be lower in cost than rheostatic control and would result in higher efficiency.

Rheostatic control offers little or no potential for advantageous use in future, economically feasible electric vehicle propulsion systems, and therefore no development of this approach was included in the E&HV Propulsion Development Project.

**Motor-generator sets.**—Motor-generator sets have been used widely for control of variable-speed motors in industrial applications. They are a relatively efficient and a very versatile means of controlling voltage at high current levels. In general, their use is most prominent in systems of 100 kW and larger, but they can also be used at lower power levels. In effect, some form of rotating electromagnetic machine or combination of machines is used as a high-power amplifier. A low-power control current is supplied to a field winding of a dc generator being rotated by a motor connected to a constant-voltage source. The output of the generator will vary as the control current is varied. Depending on the concept used, power gains exceeding 100 can be achieved between control winding and dc generator output power. The dc generator output power is fed to the variable-speed dc motor. Thus the speed and torque of the dc motor can be controlled by the low-power control of the generator field.

There are many approaches to using rotating electric

machines as power amplifiers for control of variable-speed motors. Some of these are the Amplidyne, the Ward-Leonard, and the Rototrol systems. Other concepts use brush position shifting to vary the output of a dc generator. All of these concepts, and others, are covered extensively in the literature. In general, motor-generator control of a dc motor in the power range applicable to electric vehicles is more efficient than rheostatic control but also more expensive and heavier. If a lightweight motor-generator concept could be developed for electric vehicle propulsion, it might be attractive because of its ruggedness and its use of relatively simple technology familiar to a large segment of the technical trades. These features could outweigh any shortcomings in efficiency and weight when compared with the more sophisticated electronic chopper controllers described later in this report.

These potentially attractive features led to the inclusion of a motor-generator-based controller in the E&HV Propulsion Development Project. This controller, demonstrated in principle and designed as an engineering model by the Franklin Research Center, is described in detail in reference 38. Briefly, as shown in figure 33, it consists of a motor-generator set connected to run from the dc source (battery) and to generate a voltage in the traction motor-armature circuit that can oppose or add to the source voltage. When the traction motor is at rest, the generator terminal voltage is controlled through its field to be exactly equal to the battery voltage and no current flows in the traction motor-armature circuit. To accelerate and run the vehicle, the generator field is decreased, this reduces the generator voltage and allows the difference between battery and generator voltage to be applied to the traction motor. Current flowing "backwards" through the generator makes it a motor and its drive motor a generator, recirculating the absorbed power back to the battery. When the generator field is reversed, the generator voltage adds to the

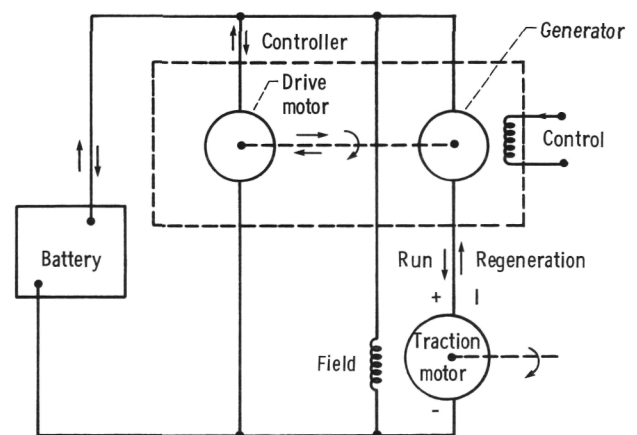


Figure 33. — Schematic diagram of Franklin Research Center dc motor controller.

available battery voltage to provide motor speed above the base speed.

For regenerative braking the generator field is increased; this raises the sum of the traction motor voltage and the generator voltage above the battery voltage, feeds current back to the battery, and reverses the torque on the traction motor. The power required to boost the traction motor voltage is circulated from the battery through the motor-generator set. This mode can also be used to reverse the rotation of the traction motor without the need for heavy electrical contactors. The engineering model design integrates both motor and generator on a single two-bearing shaft. The control is designed to produce a controlled bidirectional  $\pm 48$ -V dc output from the generator and thus permit full control of a 96-V dc traction motor from a 48-V battery. The controller is predicted to weigh 63.5 kg and have a peak efficiency of 90 percent in random driving modes and 96 percent during the SAE 227a Schedule D driving cycle.

Although these predicted values for weight and efficiency are better than those for earlier motor-generator controllers, they were not sufficiently attractive (when compared with electronic chopper controllers) to warrant further development in the E&HVP Propulsion Development Project. Further innovation in the motor-generator approach may be possible that will make it more competitive with the electronic choppers, but the degree of improvement beyond that predicted for the Franklin design is highly speculative.

**Choppers.**—Except for battery switching, choppers can be the most efficient means of controlling a dc propulsion motor. But, unlike battery switches, choppers can be used to control the speed and torque of the motor smoothly from zero to their maximum values. The advent of power semiconductors in the 1960's made possible the design of these controllers for industrial electric forklift trucks. Chopper controllers are now almost exclusively used in these trucks as well as in a large number of other electric vehicles such as those in the DOE E&HVP program and other application and demonstration programs. They are also finding increased application in other battery-powered electric vehicles such as airport support equipment (tugs and baggage trucks). Choppers can be, and are, used for control of both the armature and the field in dc motors.

**Operating fundamentals:** "Chopper" is the popular term applied to switched-mode, buck or buck-boost dc-to-dc converters. These converters function on the principle of switching power from a constant source (battery) on and off at a frequency high enough so that the load (motor) responds to the average value of the switched voltage. For instance, if the "on" time and "off" times are equal, the average voltage applied to the motor is about one half the source voltage. By adjusting the on and off times, the average output voltage from the converter can be varied from zero to near full source

voltage. The ratio of on time  $t_{on}$  to "on + off" time  $T$  is termed the "duty cycle."

The simplified circuit of figure 34 includes the essential conceptual elements of chopper control for a motor. With the switch S closed, current will flow from the battery to the motor, increasing at a rate determined by the difference in voltage between the battery and the back electromotive force (emf) of the motor together with the total circuit inductance and resistance. When S is opened, battery current ceases and motor current decays gradually through the free-wheeling diode D. The rate of motor current decay is determined by motor inductance and resistance. The battery current will have the general waveform  $i_b$ ; the motor current  $i_m$ ; and the diode current  $i_D$ . When the switch is again closed on the following cycle, current in D stops and battery current starts again. The motor voltage will have the general waveform  $v_m$ . The ideal switch is lossless and the chopper tends to function as a dc transformer. That is, the product of average battery voltage and current is approximately equal to the product of average motor voltage and current ( $\bar{V}_b \times \bar{i}_b = \bar{v}_m \times \bar{i}_m$ ). The means of controlling switch operation can be quite varied, ranging from free-running oscillators to constant-frequency switching to controlled variable frequency—all giving duty-cycle control. Some chopper designs use a variable switching frequency, depending on duty cycle, between 50 and 500 Hz. Others operate at relatively constant switching frequencies up to several thousand hertz. The selection of switching frequency is a design consideration and depends on the switching device's speed of turn-on and turnoff, acceptable losses during the switching interval, and other circuit parameters. The switching devices and their limitations will be discussed in the next subsection.

Chopper control of field current in a shunt motor is similar to the armature control just described. The field winding would simply replace the armature and series field in figure 34.

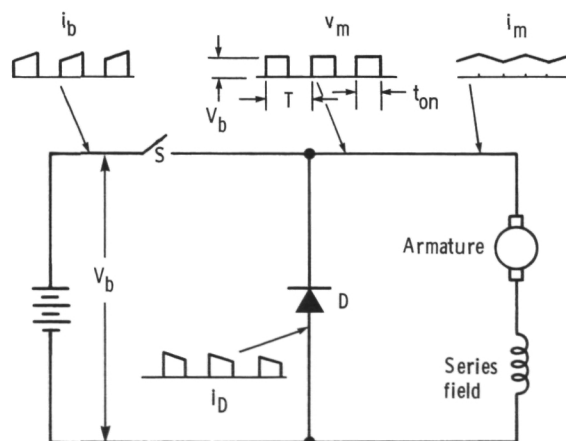


Figure 34. — Essential elements of a chopper-controller dc motor.  
 $v_m \sim V_b t_{on}/T$ ;  $i_m \sim i_b T/t_{on}$ .

As figure 34 shows, chopper control of a motor results in battery and motor currents that can have large ac components (ripple). The ac components of current flowing in both the battery and the motor result in greater losses than the same-amperage smooth, ripple-free, average currents. The increased losses in motors have been investigated both analytically and experimentally as described in references 7 and 17 to 20. These losses vary with chopper operating duty cycle and motor load conditions, the greatest losses occurring near the 50-percent-duty-cycle condition. Ripple-induced losses in batteries have also been investigated (ref. 39), but the overall results are not yet clear. These losses in the battery raise the battery operating temperature somewhat above that experienced with smooth dc and thereby make it more electrochemically energetic, which in turn tends to cloud test results. However, the ripple losses that resulted in battery temperature rise are losses that would not be encountered with smooth dc. They therefore will result in some as yet undefined reduction in battery charge-discharge efficiency and at the same time increase the total energy that can be taken from the battery.

The chopper of figure 34 can be reconfigured to the circuit of figure 35 to allow controllable regeneration in an electric vehicle. The circuit of figure 35 is a simplified "boost" configuration and is used here only as an example. There are many other means by which controlled regeneration can be accomplished, and the reader is referred to the literature for these. In figure 35, when switch S is closed and the motor is being supplied with mechanical energy, current  $i_s$  will build up in the motor shorted by S, and store energy in the motor inductance and any auxiliary inductance. When S is opened, the current through the shorting path stops and, because of the stored inductive energy, the voltage at A rises to a value that will cause D to be forward biased and discharge the stored inductive energy into the battery. When S is again closed, the cycle repeats. As the motor

speed is decreased, the on-off times of S can be varied so that voltage peaks can be developed at A such that regenerative energy flows from the motor to the battery in a controlled manner.

**Switching devices:** Although mechanical devices have been used in chopper circuits in the past (vibrators for vacuum tube automobile radios and early automobile ignition systems), the main switching device for practical chopper controllers for electric vehicles today is a switching power semiconductor. Today's prime contenders are (1) the unidirectional thyristor (also called a silicon-controlled rectifier, or SCR), (2) the bipolar power transistor, and (3) the field-effect power transistor.

SCR's are well established in the industrial motor control and power-conditioning fields and are readily available in current and voltage ratings needed for electric vehicle motor controllers. They are well understood (having been commercially available since the early 1960's), rugged, and relatively low cost (\$0.2 to \$0.3/A in small quantity). SCR-based chopper controllers are produced by a number of manufacturers (ref. 40) for industrial forklift trucks and electric vehicles. SCR's unfortunately have two characteristics that adversely affect their application in dc choppers. First, and most importantly, they are bistable semiconductor devices. They can be turned on by a low-power trigger pulse, but once on, they can only be turned off by interrupting the current flow through the device. Turnoff in a dc chopper therefore requires auxiliary circuitry that temporarily bypasses the load current around the conducting SCR and thereby allows it to turn off. This auxiliary circuitry is commonly referred to as the "commutation" circuit and can take many forms depending on the designer's choice and the application requirements. Most commutation circuits include a means to reverse bias the SCR to speed recovery of its blocking capability. The second adverse characteristic is the time it takes for an SCR to fully turn on and turn off. Power is lost during the turn-on and turnoff intervals because current does not cease or start instantaneously and the voltage across the SCR cannot change instantaneously. This power loss, together with the time required for turn-on and turnoff, limits the chopping repetition frequency in simple SCR dc choppers to frequencies below 1000 Hz. More complex circuits have been developed that allow higher frequency (ref. 41), but these are more costly. Ongoing development of gate-turnoff SCR's may eventually reduce the problems involved in SCR application to dc choppers.

Spurred on, in part, by the limitations of SCR's, development of fast-switching bipolar power transistors is progressing rapidly in industry and government. Until only recently, available transistors needed to be operated with many in parallel in order to switch the current levels encountered in electric vehicle chopper controllers for motor armature control. Paralleling entails special pro-

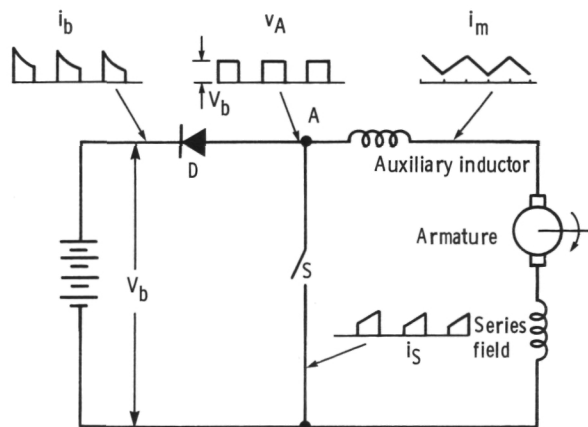


Figure 35. - Simplified chopper in a voltage boost configuration for regeneration.

visions that add complexity. Field choppers can use single low-power transistors. New power transistors that can rapidly switch current in the 200- to 300-A range are becoming available. Although still relatively expensive (\$1.0 to \$1.4/A in small quantity), their cost is declining rapidly. It is expected that eventually, as the markets develop, power transistors will be cost competitive with SCR's. Power transistors can be turned on and off rapidly by relatively low-power drive circuits. These drive circuits are complex but result in low-loss switching. The switching time of available transistors will allow chopping repetition rates up to 20 000 Hz.

Field-effect power transistors with current capabilities in the 10- to 20-A range are available, and higher current devices are under development. Field-effect transistors can be turned on and off with very low-power drive circuits since they are basically voltage-controlled devices. They can also be efficiently operated at frequencies up to 50 000 Hz. Their cost, approximately \$2.5 to \$6.0/A in small quantity, is higher than that of transistors of equivalent current capacity, but their high speed offers benefits. The present current capability of single field-effect transistors limits their use in electric vehicles to motor field control unless paralleling is used. Field-effect transistors can be easily paralleled to reach higher current levels, but the number of today's transistors that must be paralleled to control armature current in an electric vehicle is prohibitive because of reduced reliability and increased complexity. Ongoing development is sure to increase the current capability and widen the applicability of field-effect power transistors to electric vehicle chopper controllers.

**New chopper controller development.**—The Electric and Hybrid Vehicle Propulsion Development Project included the development of an advanced chopper controller for dc shunt-wound motors. This development, described in reference 42, was conducted by the Huntsville Electronics Division of the Chrysler Corporation. The controller in its final design has a single high-power transistor rated at 400 V and 300 A in the armature chopper and three paralleled field-effect transistors in the field chopper. Both armature and field choppers operate at 20 000 Hz. Test results from the engineering model hardware indicate controller efficiency above 95 percent. Because of the high-frequency operation, small filters are included inside the controller package to limit battery and motor current ripple to a near-negligible 5 A rms. Such filtering in low-frequency choppers is impractical because of the size of the inductors needed. Another benefit of the high-frequency chopping is negligible audio noise. Low-frequency choppers characteristically emit audio noise of a frequency and intensity that is objectionable to many people. The engineering model of this advanced chopper controller includes a microprocessor to control the operation of the armature and field choppers as well as to

control the automatic reconfiguration of these choppers to provide charging of the vehicle traction battery. Although prohibitively expensive at this time, this chopper controller demonstrates what can be accomplished with the new power transistors now becoming available. The continued development of these transistors and their declining cost will allow still better chopper controller designs suitable for volume production at acceptable cost before the end of this decade.

### Alternating-Current Motor Controllers

In contrast to those for dc motors, control concepts for variable-speed ac motors are still evolving. The fundamental requirements for variable-speed ac motor control are well understood, and many technical papers and reports have been published on the subject. The reader is referred to that literature for details of variable-speed ac motor control beyond the brief discussion presented here. The discussion of ac controllers in this report is limited to controllers operating from a relatively fixed-voltage dc source (batteries). Operation of ac motors from an ac source is not relevant to electric vehicle propulsion.

The control of ac motors in battery-powered, wide-speed-range propulsion systems generally requires inverter, or inverter-like, power electronics as shown in figure 36. For purposes of this report ac controllers are treated in two classifications: those for induction motors and those for synchronous motors.

**Induction motor controllers.**—The control of an induction motor in a vehicle propulsion system requires the controller to supply polyphase ac voltage or current at variable frequency and voltage. The manner in which these parameters need to be varied is discussed in the section describing induction motors. This section deals with the major power electronic schemes to obtain controlled, variable-speed operation.

Although two or more phases can be used in ac motors (refs. 27 and 28), three-phase systems are the most common by far. The central circuit of a controller for an induction motor is a dc-to-ac inverter. Such an inverter typically consists of an array of switches placed between a dc source (battery) and an ac load (motor) and controlled

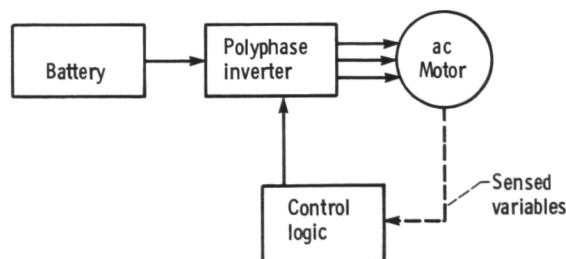


Figure 36. — Block diagram of elementary ac motor control.

such that the motor sees an alternating voltage and current. The operation of these switches to form an elementary three-phase inverter is shown in figure 37. In practical circuits, the switches of figure 37 will be either SCR's or transistors, both of which are unidirectional. Therefore they must be paralleled by rectifiers, as shown in figure 38, to allow the reactive current encountered with motor loads to flow in the inverter. The relative merits and characteristics of SCR's and transistors as switching devices were discussed in the section Choppers.

By simply varying the switching rate the frequency of the inverter output voltage can be varied over a wide continuous range. Thus the basic requirement of motor speed control is satisfied. The second key requirement for motor speed control is the capability to vary the applied

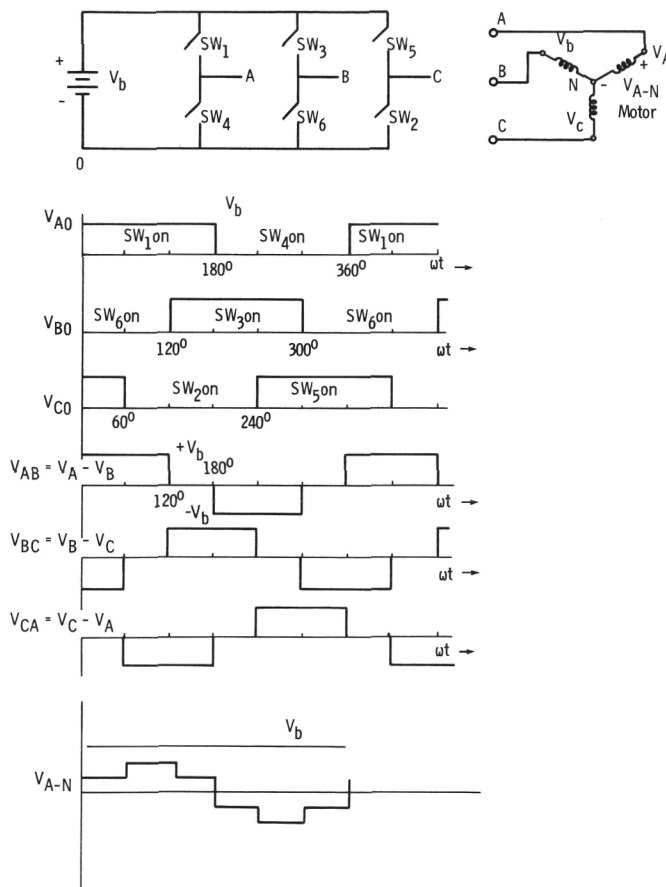


Figure 37. – Elementary three-phase inverter switching sequence.

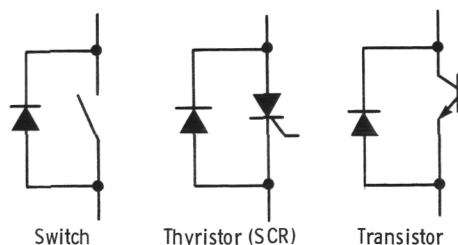


Figure 38. – Switching devices with reactive diode.

motor voltage as the frequency is varied. Note that the simple waveforms displayed in figure 37 do not satisfy this requirement since their amplitudes are fixed by the source voltage amplitude  $V_b$ .

One technique for providing this variable-voltage capability is to add a power conversion stage (chopper) between the battery source and the inverter input to adjust the inverter input voltage. Thus the amplitudes of the figure 37 waveforms become variable rather than fixed values. To avoid the cost and power loss of introducing this additional power stage, an alternative approach can be adopted that achieves this independent voltage control in the inverter stage itself. This is accomplished by using pulse-width modulation (PWM) techniques to increase the sophistication of the inverter-stage switching algorithm. Such PWM algorithms provide the drive designer with a powerful tool for shaping the inverter output waveforms.

Since the voltage waveforms delivered by the inverter are nonsinusoidal, undesirable harmonic components are present in the voltage waveforms supplied to the motor. These harmonics produce pulsating torques and losses in the motor without contributing to the average torque and hence reduce the system efficiency. Sufficient degrees of freedom are inherently provided by the PWM algorithm to permit the concentration of the energy of the inverter output voltage waveform in the fundamental frequency component. The amplitude of the fundamental component can be independently adjusted by means of a duty-cycle control as shown in an elementary manner in figure 39.

In controllers for wide-speed-range induction motor drives, pulse-width modulation can be used from zero speed up to the maximum speed of the drive. Designers of electric vehicle propulsion systems, however, have preferred to use PWM up to some predetermined base speed. At base speed the duty cycle would be such that waveforms similar to those in figure 37 would be produced, and the ac voltage magnitude would be at its maximum—as determined by battery voltage. Above base speed, frequency only is increased to obtain greater speed. As explained in the section Induction motors, torque is controlled by varying the “slip” of the motor. This is accomplished by having the inverter output frequency slightly higher than that equivalent to rotor synchronism for motoring or slightly lower for regeneration.

The induction motor control described previously

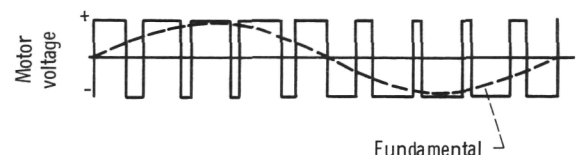


Figure 39. – Pulse width modulation of inverter output voltage.

provides the motor with a controlled ac *voltage*. Motor current is determined by the applied shaft load together with circuit and motor electrical parameters. An alternative approach is to provide the induction motor with a controlled ac *current* at speeds below base. This approach, though somewhat more complex, allows direct control of inverter and motor current and thereby nearly eliminates inverter damage from uncontrolled current peaks.

Because variable-speed induction motor drives have an undesirable torque instability near zero speed, they cause a jerky start. It appears that this is more of a problem with the voltage output inverters than it is with the current output type. The cause of this instability is not fully understood, but some studies indicate that the resistance and inductance of the motor rotor and stator have a significant effect on stability at very low speed. Low-speed stability must be carefully considered during the development of any induction motor propulsion system.

The induction motor is a reactive load and draws reactive current from the inverter. The inverter can conduct the reactive current by means of the opposite-polarity rectifiers in parallel with the semiconductor switches (fig. 38). The battery, however, does not readily accept these reactive currents because it sees them as a high-frequency ac component. Because battery impedance to this component is high, low-impedance capacitors must be placed in parallel with the battery to provide a suitable path for the ac component in the inverter input current. These capacitors are also essential for regenerative operation with induction-motor electric vehicle propulsion systems.

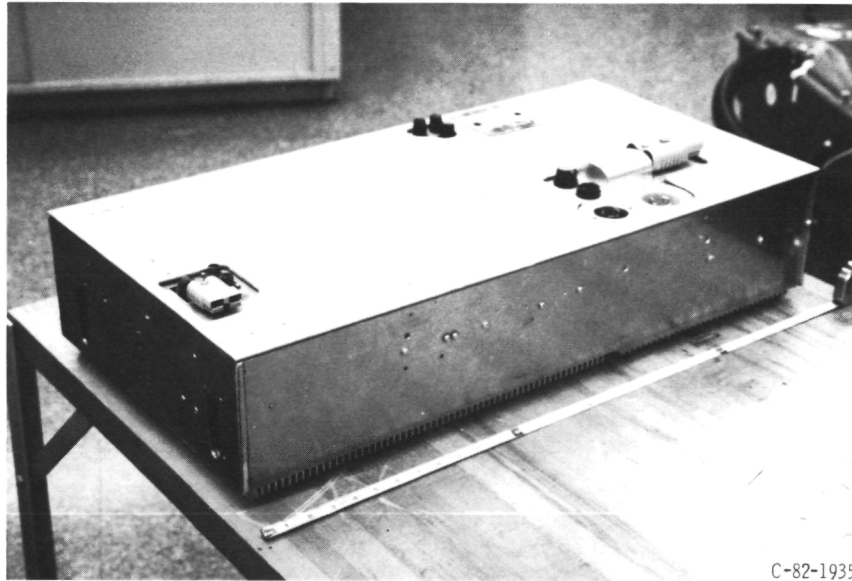
The DOE E&HV program has included development of three controllers for induction-motor propulsion systems. The Eaton Engineering and Research Center has completed phase II of an ac propulsion system that produced a second-generation controller and culminated in an in-vehicle test. The Eaton controller, a voltage output type, is shown in figure 40. It uses power transistors in a Darlington configuration as the switching devices in the inverter. This controller is air cooled, weighs approximately 43 kg (95 lb), and has demonstrated an efficiency of 96 percent at 11 kW. The Eaton design approach and development results are fully described in references 12 and 43. Both the phase I and phase II systems have low-speed torque instabilities, but Eaton feels that this problem can be resolved through modifications in the system control logic.

In another effort, Gould Laboratories has brought the development of an SCR-based controller for a propulsion induction motor to the engineering model stage. The Gould development was aimed at the controller not at a complete propulsion system. The power inverter stage of the resulting engineering model ac controller is shown in figure 41. Like the Eaton controller, the Gould approach

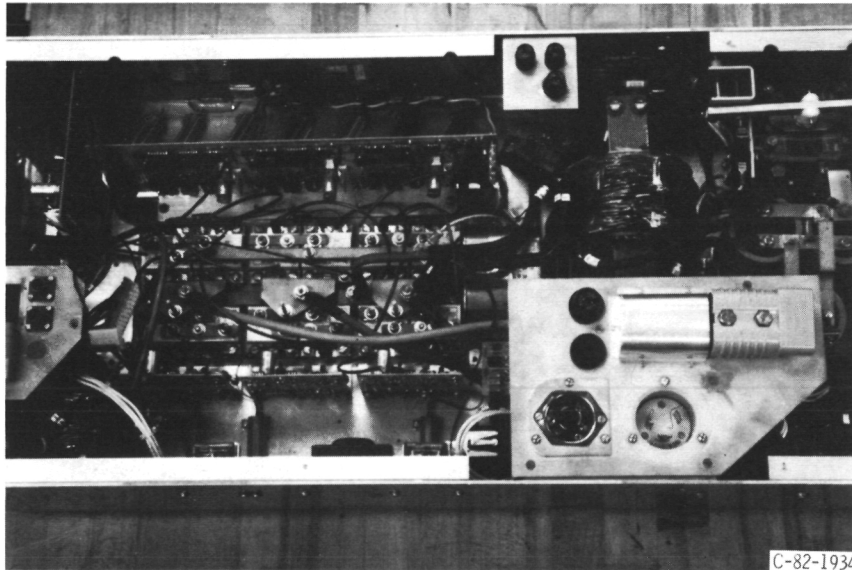
provides a variable-frequency, variable-voltage output and has exhibited low-speed torque instability. But it uses rugged, low-cost (\$80 to \$100 each) SCR's as the inverter switching devices. This controller model is also air cooled, weighs approximately 47 kg (103 lb) without low-level logic, and has demonstrated 90 percent efficiency at 11 kW in laboratory tests. Low-level logic circuitry when suitably packaged might be expected to add about 5 to 8 kg (11 to 18 lb). It should be pointed out that the Gould controller incorporated battery charging capability that made use of the same power components used for inversion. It was also capable of a maximum power of 33 kW to provide improved acceleration beyond that required by the power-time curve of figure 10. The efficiency of the SCR-based ac controller is somewhat less than that of a transistor-based controller. This is to be expected because the auxiliary circuitry necessary to turn off (commutate) the SCR's generates losses not found in transistor circuits. References 30 and 44 give complete details on the Gould controller.

As can be seen from the internal views of figures 40 and 41, the transistor inverter has more parts than the SCR inverter. The reasons are that presently available transistors must be paralleled to obtain adequate current capability in these controllers and they must be protected from high voltage and power spikes during switching times. Because of fewer and lower cost power components, the SCR-based approach should be lower in cost at this time.

The third ac induction motor controller in the DOE E&HV program differs from the two discussed above in that it provides a variable-frequency, variable-magnitude *current* to the motor. This controller is being developed by the General Electric Corporate R&D Center. The GE inverter uses developmental power Darlington-configured transistors as the switching elements. These transistors are predicted to have a very low cost in volume production and may allow a high-performance induction motor propulsion system to be developed that would be economically attractive. Such transistors would benefit all switching controllers. Laboratory tests with the GE controller and the specially designed induction motor shown in figure 20 indicate no low-speed torque instability with this combination. The GE controller, shown in figure 42, was not brought to the same level of package design as the Eaton or Gould controllers but was sufficiently complete to allow meaningful tests. The design and operating principles demonstrated in this controller are being applied to the development of a complete advanced integrated ac power train being developed by the Ford Motor Company and GE as part of the Electric and Hybrid Vehicle Program. This power train will include an oil-cooled motor integrally housed in a multiratio automatic transaxle and an air-cooled inverter that will use newer developmental, low-cost power transistors.



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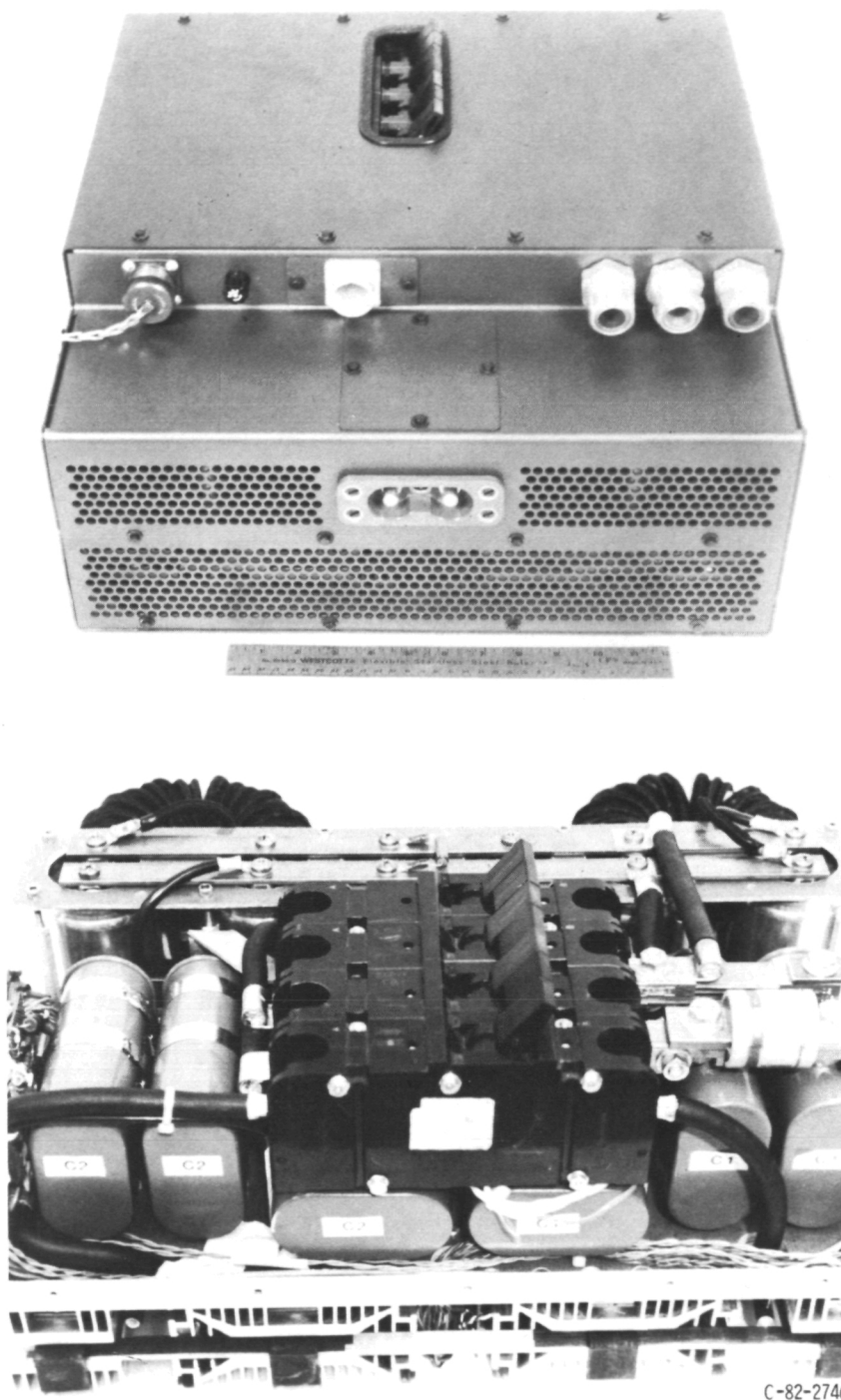
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Figure 40. - External and internal views of Eaton phase II ac controller.

The technical practicality of controllers for induction motor electric vehicle propulsion systems is nearing certainty. However, significant development remains to be completed in controller design and switching devices before the low cost, ruggedness, and simplicity of induction motors can be economically applied to electric vehicle propulsion systems. The three controller developments differ in details of switching device and control methods but are similar in that their power stage is a three-phase bridge inverter. As development progresses, it is reasonable to expect that the size differences presently existing between the various hardware designs will diminish because size is primarily determined by the inverter configuration and cooling

methods. Performance differences may also decrease as new SCR developments evolve that allow lower loss switching than that presently attainable. Inverter efficiencies in the mid-90-percent range at and near rated power can be expected. Cost, efficiency, and size of induction motor controllers are noticeably affected by system voltage. Higher voltage generally results in higher efficiency, and voltage capability in semiconductors is now more available than current capability. Therefore the induction motor controllers discussed have all been designed to operate with battery voltages above 120 V. Eaton's was designed for 192 V and Gould's for 132 V. The Ford/GE system is being designed for 204 V.

**Synchronous motor controllers.** - Controllers for



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Figure 41. — External and internal views of Gould SCR ac controller.

excited synchronous ac motors have a power circuit very similar to controllers for induction motors. The most common circuit used is a three-phase, switch-mode bridge inverter. However, control methods to sequence switch operation in the bridge for synchronous motor variable-speed operation are significantly different than those for the induction motors. For the purposes of this

report the combination of a synchronous motor and its controller has been termed an “electronically commutated (EC) motor.”

The essential elements of an EC motor are shown in figure 23. The switching of the electronic switches in the inverter is controlled by gating circuitry synchronized to signals from the shaft position sensor or other field-

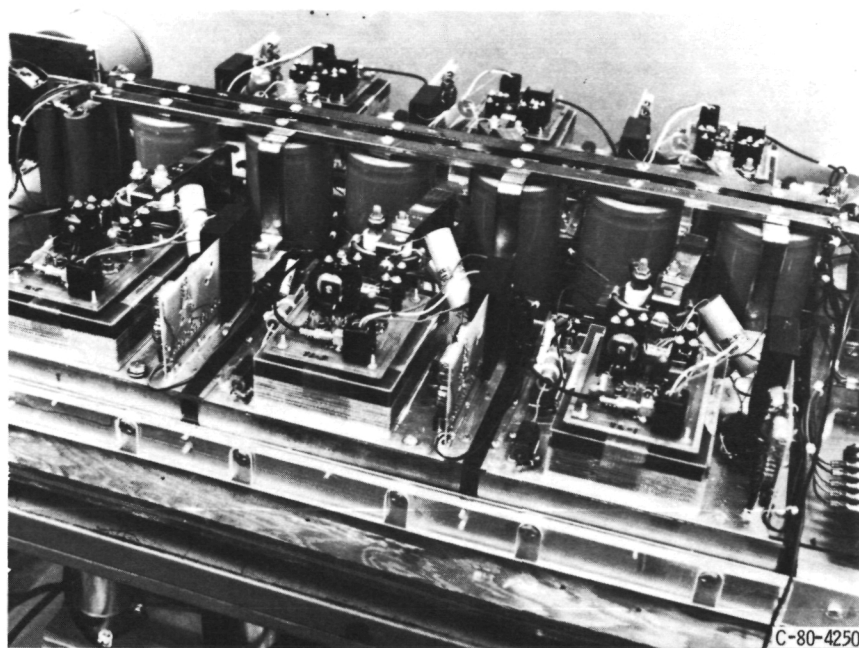


Figure 42. — GE transistor-based ac induction motor controller.

position sensing means. The combined operation of inverter, gating, and position sensor is analogous to brush commutation in conventional dc motors. The converter (chopper) controls the voltage or current supplied to the motor and, in some designs, provides proper operation of the inverter at low speeds.

Controllers for unexcited synchronous motors such as the reluctance motor are quite varied, and their design depends on motor configuration and application. They, like other ac motor controllers, generally use switch-mode power electronics but in much wider circuit variety. The early developmental stage of unexcited synchronous propulsion motors and their controllers at this time precludes detailed discussion of them in this report. The reader is referred to the developing literature on this subject. Reference 37 is a good starting point.

The DOE E&HV Propulsion Development Project included two different approaches to controllers for permanent magnet synchronous motors. These controllers were integral parts of the electronically commutated motor developments by AiResearch and Virginia Polytechnic Institute (refs. 32 and 33). Functionally these two controllers are very similar, but they differ substantially in how they operate. SCR's are used in the inverter portion of the AiResearch controller; high-power transistors are used for this function in the VPI controller.

The controller using SCR's as inverter switches is shown schematically in figure 43. SCR's have an advantage over power transistors in that SCR's are readily available in any current and voltage range of interest for electric vehicle applications, are very rugged,

and are presently much less expensive. The major problem is that the SCR can be difficult to turn off. Turnoff, or commutation, requires that the current through the device be reduced to zero by removing the applied voltage (natural commutation) or reversing the voltage (forced commutation). In the motoring mode the SCR's are turned on in the proper sequence by using rotor position information determined from the near-sinusoidally varying back voltage generated by the synchronous motor. The back voltage of the machine is also used to commutate the SCR's by a technique described in reference 45. This technique is based on the fact that a reverse voltage will appear across the SCR to be commutated if the next SCR in the sequence is turned on at an appropriate time. At low speeds the back voltage is too low to properly turn off the SCR's. Therefore an optical shaft-position sensor is used in conjunction with logic circuitry to turn off the current control chopper  $Q_M$  for a period of time sufficient to allow the corresponding SCR to turn off by natural commutation. Transistor chopper  $Q_L$  may be included, as an option, to achieve forced commutation. It has been found that elimination of this transistor results in some power loss at very low speeds. In the motoring mode of operation, switch  $SW_1$  is closed. Power is supplied via the choke  $L_1$  to the inverter bridge  $Q_1-Q_6$ . The current level is controlled by the switching action of  $Q_M$ . In the regenerative mode, switch  $SW_1$  is open, and the SCR's are operated as a three-phase bridge rectifier. The voltage is boosted to an appropriately high level by  $Q_M$ ,  $D_1$ , and  $L_1$ . The SCR controller in breadboard form is shown in figure 44. This version weighs 36 kg (79 lb). In a production prototype,

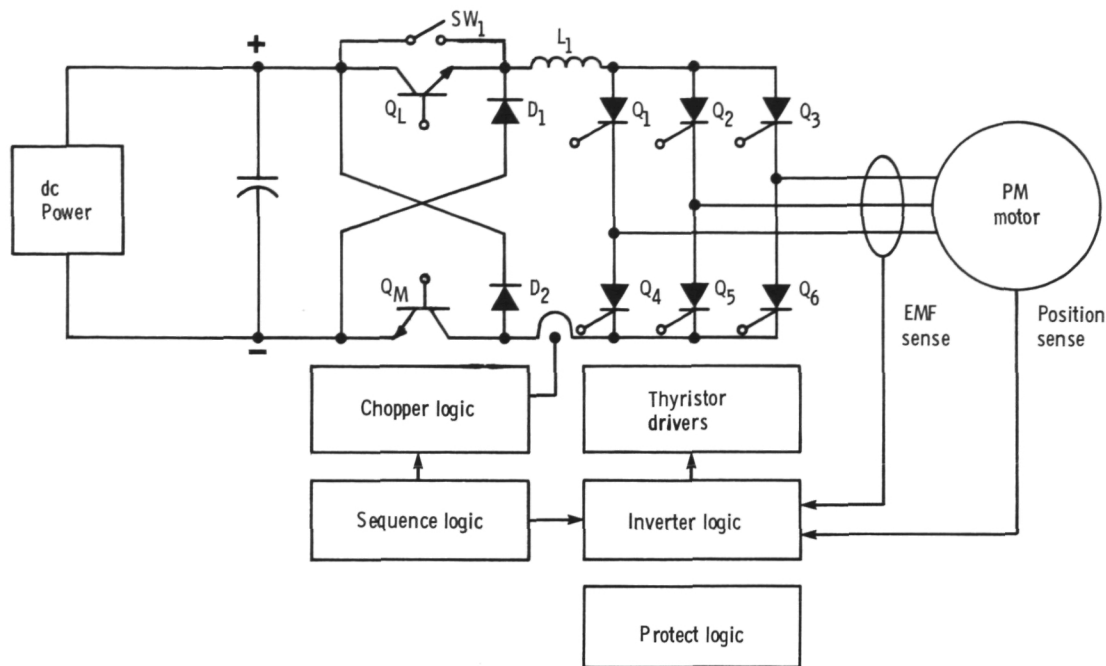


Figure 43. – Elementary schematic diagram of an SCR-based controller for synchronous motors.

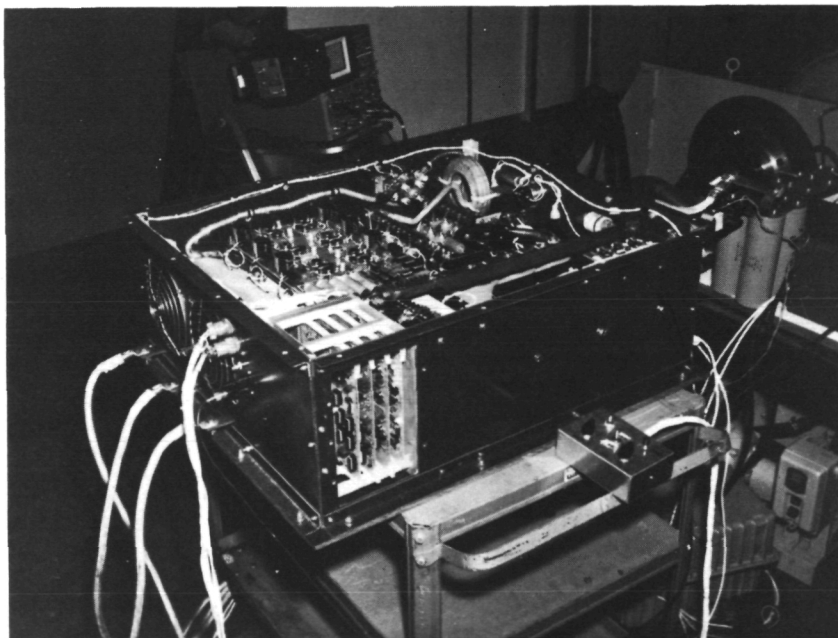


Figure 44. – AiResearch SCR-based controller for permanent magnet motor – laboratory test hardware.

its weight should be about 27 kg. The laboratory tests indicate a controller efficiency above 90 percent over a broad operating range, with a maximum of about 95 percent at rated load.

The controller using power transistors as inverter switches is shown schematically in figure 45. Transistors  $Q_M$  and  $Q_B$  make up a two-quadrant converter (chopper) and control power flow in either direction. During the motoring mode the current is regulated to provide the

torque commanded by the vehicle operator. The choke  $L$  is included for additional inductance to reduce current ripple. The regulated current is switched by the three-phase transistor inverter bridge to provide the power to the motor armature windings in the proper sequence for motor operation. The dashed line in figure 45 shows the current path for phase A-B in the motoring mode. In this case, transistors  $Q_1$  and  $Q_6$  are turned on. Transistor operation is controlled by the position sensors mounted

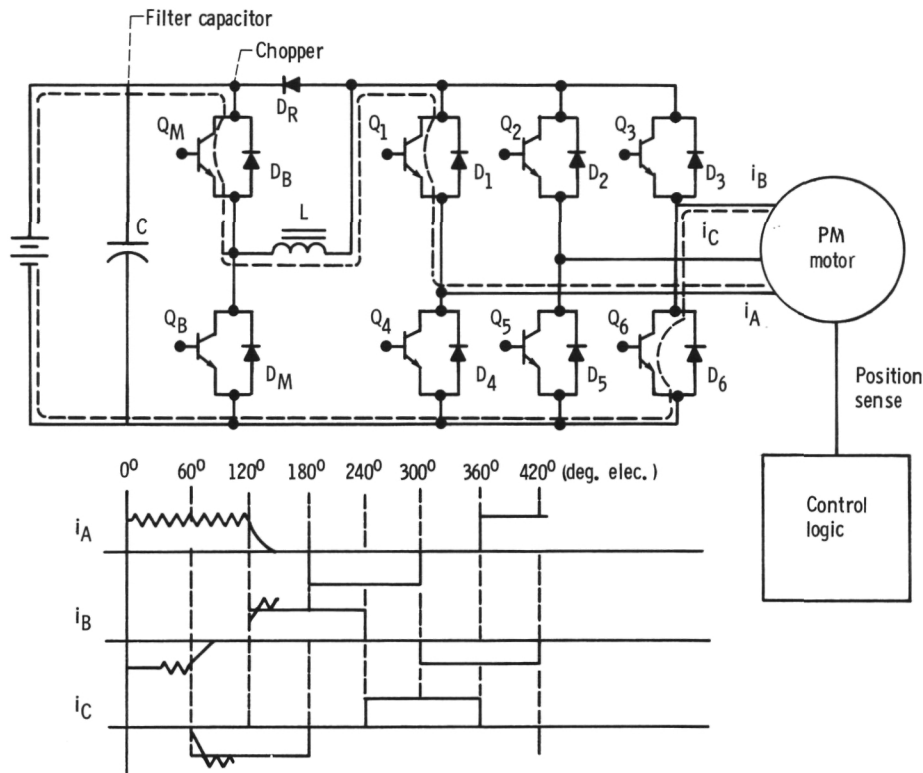


Figure 45. - Elementary schematic diagram of a transistor-based controller for synchronous motors.

on the motor shaft. In the regenerative mode, diodes  $D_1$  to  $D_6$  act as a three-phase, full-wave bridge rectifier allowing power to flow from the motor to the battery. The generated voltage of the motor is boosted by the action of the chopper transistor  $Q_B$  and the choke  $L$  to overcome the battery voltage. Inertial energy of the electric vehicle can be returned to the battery in this manner. A description of this type of controller, as well as additional details of the transistor-based inverter discussed here, is given in reference 33.

The completed breadboard version of the transistor-based controller, shown in figure 46, weighs about 41 kg (90 lb). However, with the use of custom-designed heat sinks and attention to packaging details, this weight could be reduced to about 27 kg, the same as projected for the SCR-based controller for synchronous motors. The laboratory tests on this transistor-based controller indicate a total motor-with-controller efficiency of 87 percent at rated power with the samarium-cobalt motor. Controller efficiency was well above 90 percent over a broad operating range.

These two controllers (SCR based and transistor based) could also be applied to the disk type of permanent magnet, synchronous motors with minimum modifications to accommodate differences in motor impedances. Certainly, other concepts for electronically commutated motors have been, and are being, developed for other applications. The reader is referred to the literature for

further information on these developments. The two electronically commutated motors developed in the DOE E&HV program can be considered to be representative developments for electric vehicle applications.

As the schematic diagrams of figures 37, 43, and 45 show, the main element of a synchronous motor controller, the switch-mode inverter, is nearly identical to that of an induction-motor controller. The main difference between these two controllers is how the inverter is controlled. The inverter in an induction motor controller must provide ac voltage at variable frequency, variable voltage, and controlled slip. The inverter in a synchronous motor controller needs only to be an array of switches operating in synchronism with the motor rotor and to provide a means of motor current control. Control of a synchronous motor would seem to be a simpler task than control of an induction motor. Indeed, experience to date indicates that it is. Low-speed torque instability has not been a problem in the electronically commutated motors. Also, controllers for PM synchronous motors are expected to be more efficient than induction motor controllers when compared on an equal basis, because the synchronous motor controller does not have to handle motor excitation power. Ultimately, low-level and logic circuitry will be committed to integrated circuits and the physical differences between induction motor controllers and synchronous motor controllers will diminish. Advances in power

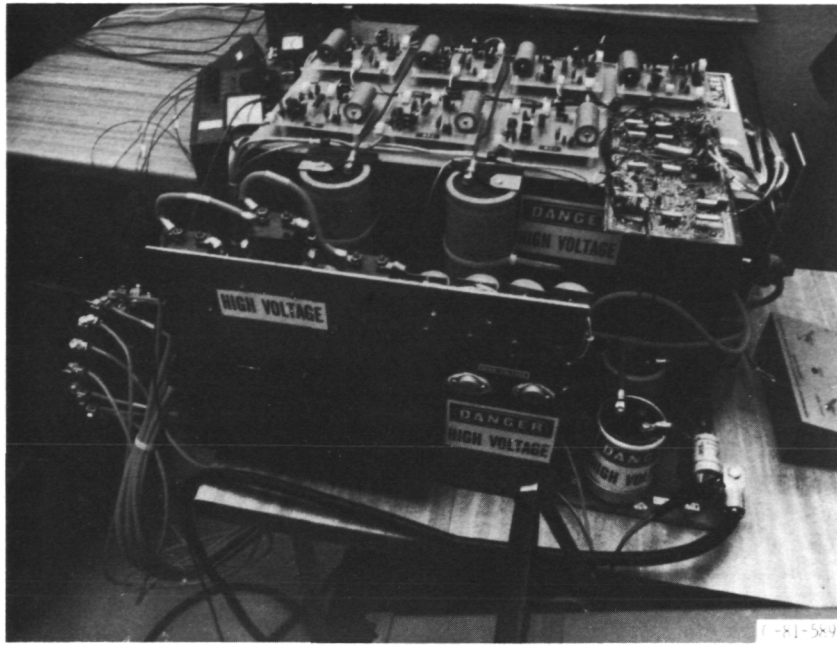


Figure 46. — VPI transistor-based controller for permanent magnet motors — laboratory test hardware.

electronic technology that benefit the induction motor controller will also benefit the synchronous motor controller.

### Controller Technology Improvements

As is the case for motors, controller technology development in the DOE E&HV program to date has resulted in innovative and efficient designs for both dc and ac controllers. Controller concepts will continue to be refined to accommodate expected markets. As new semiconductor devices such as field-effect power transistors and gate-turnoff SCR's become available, it can be expected that controller designs will be evolved to take advantage of them if a market is seen. In any event, further development is needed to evolve practical, vehicle-oriented controller packaging concepts — present controllers are too large.

Clearly, cost is now the major drawback of the high-performance ac and dc switch-mode controllers described in this report. It must be kept in mind, however, that these controllers contain virtually all of the control functions that are likely to be required for operation of an electric vehicle. The OEM cost of an SCR-based ac controller has been estimated at \$1500 to \$2500. Transistor-based versions of ac controllers are considerably more costly now but are potentially less expensive because of simpler fundamental circuitry. There is increasing interest by transistor manufacturers in low cost, high-power transistors. If power transistors with good heat transfer characteristics were to become available at a price of \$0.15/A, a figure considered to be achievable, transistor-based ac controllers as described

here could be produced at an OEM cost of about \$600 per unit. The total cost of an ac motor and controller combination would then be under \$1000 in 1982 dollars. A dc chopper for motor control will cost considerably less than the ac controllers because the chopper uses fewer power semiconductors. It would be reasonable to expect a high-performance dc chopper controller to be of the order of one-half the cost of an ac controller. Of course, the dc motor may be twice as costly as an ac motor. Cost therefore is a time-dependent parameter. The relative economic attractiveness of the various controller concepts will vary as time and development progress.

### MECHANICAL TRANSMISSIONS

Electric vehicles have been constructed without multiratio transmissions, but the lack of low-speed torque multiplication that the multiratio transmission affords may limit acceleration during starting, passing, and hill climbing. Under these conditions adequate torque without a ratio change requires the use of unnecessarily large motors and costly controls. Furthermore, using only voltage control with a dc motor results in less efficient motor operation over the vehicle's driving cycle than that attainable with a variable-ratio transmission. In a propulsion design study completed as part of the DOE E&HV program (ref. 46), the addition of a multiratio transmission significantly reduced propulsion system weight and lessened its cost for an electric vehicle powered by a dc shunt motor with field control. Incorporating a continuously variable transmission (CVT) and flywheel energy storage into this system

resulted in the lightest of the 17 configurations investigated and the fourth least expensive.

Although CVT's offer potential performance advantages, the bulk of transmissions used in electric vehicles are discrete multiratio units (ref. 15). Most of the multiratio units are small passenger car transmissions. In internal combustion engine cars converted to run on electrical power, existing transmissions are usually left in place. In most cases, the size and speed ratios of these transmissions are not well matched to the operating characteristics of the electric motor and vehicle.

The Propulsion Development Project of the DOE E&HV program included a significant effort in the area of multiratio transmissions. Commercially available automatic transmissions were tested extensively to provide performance data to the developing electric vehicle industry. New automatically shifted transmissions without torque converters were designed and built, and CVT's were addressed both in design studies and hardware development.

### Discrete Ratio Transmissions

In comparison with an internal combustion engine, an electric motor maintains reasonable efficiency over broader ranges of speed and torque. However, to obtain acceptable drivability and acceptable low-speed performance with available motors and controllers, electric vehicle designers have, with increasing frequency resorted to the use of multiratio transmissions, both manual and automatic. Existing automotive transmissions are low cost, reliable, and readily available, but because they have been developed for use with internal combustion engines, selection of the best match for a given electric vehicle drive is difficult. To remedy this

situation, the DOE E&HV program included testing of existing automotive transmissions as well as development of new automatically shifted multiratio transmissions.

**Automotive transmission performance.**—A test program for small passenger car transmissions was conducted to provide technical information regarding the performance of these commercially available, high-production transmissions. The principal objective of this test program was to provide torque, speed, and efficiency curves for the test transmissions in each gear range and in both drive performance and coast performance conditions. The tests were performed in accordance with the specifications of the Passenger Car Automatic Transmission Test Code—SAE J651b. Two small conventional automatic transmissions, three automatic transaxles, an automatic transmission with lockup in third gear, and a four-ratio, manual-shift transmission for a small imported pickup truck were tested. Reports have been published on all of these transmission tests (refs. 8, 9, 47 to 51).

As shown in figure 47, conventional automatic transmissions with torque converters have the characteristic of low efficiency at low output speeds. As speed increases they reach a high, almost level, plateau of maximum efficiency (80 to 85 percent) and then tend to drop very slightly in efficiency.

Figure 48, covering two recent model automatic transaxles, further shows the automatic transmission characteristic of low efficiency at low input speeds but also reflects recent improvements made in automatic transmissions by showing efficiencies increased to about 85 to 88 percent. Note that, because transaxles include a differential as an integral part of the transmission assembly, the output speeds are taken at the differential output and are lower than those in figure 47. For this

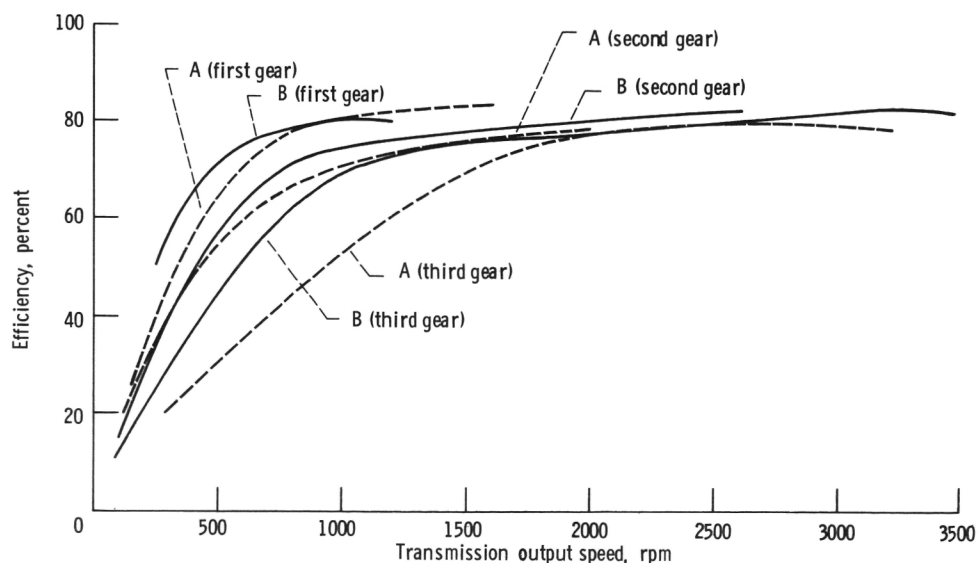


Figure 47.—Performance of two conventional automatic transmissions. Constant input torque, 122 N·m (90 lb-ft).

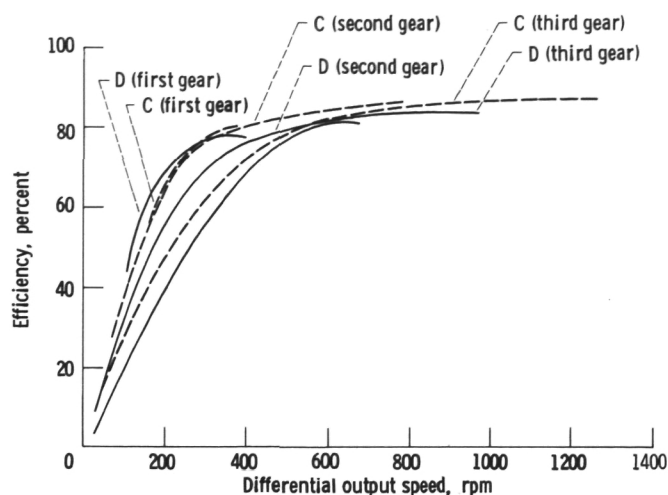


Figure 48. – Performance of two automatic transaxles. Constant input torque, 122 N-m (90 lb-ft).

reason, the differential losses cannot be separated from the transmission losses.

The curves in figure 49 show that an efficient automatic transmission can be improved by several percentage points if a provision is made to lock the output shaft to the input shaft in third gear. As shown in this figure, the elimination of the slip in the torque converter improved an 86-percent efficiency to 91 percent. As is known, however, the multiratio manual transmission is difficult to equal for efficiency. Efficiency values of approximately 95 to 99 percent were determined from tests, with the higher value occurring in fourth gear.

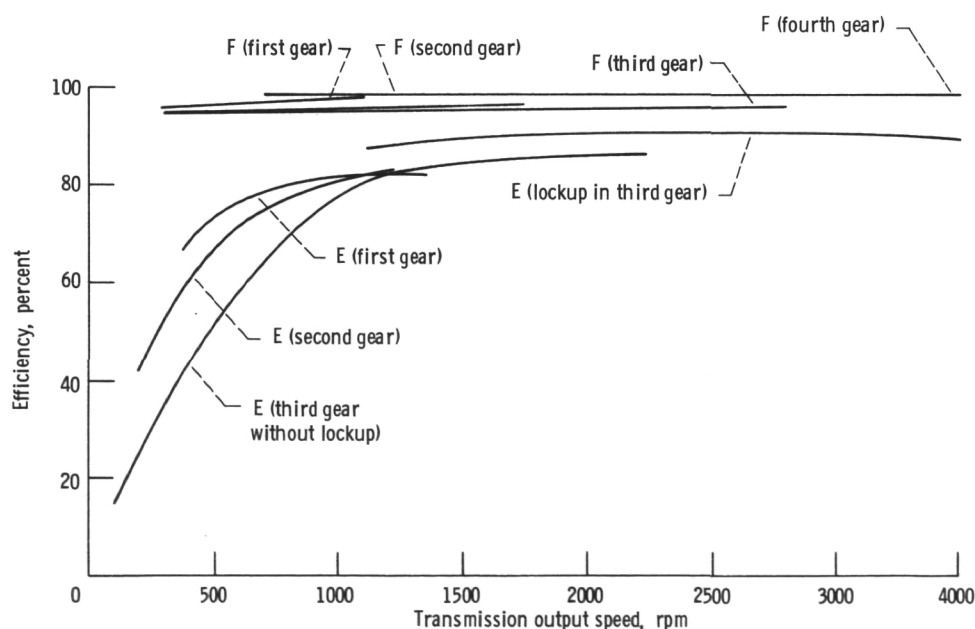
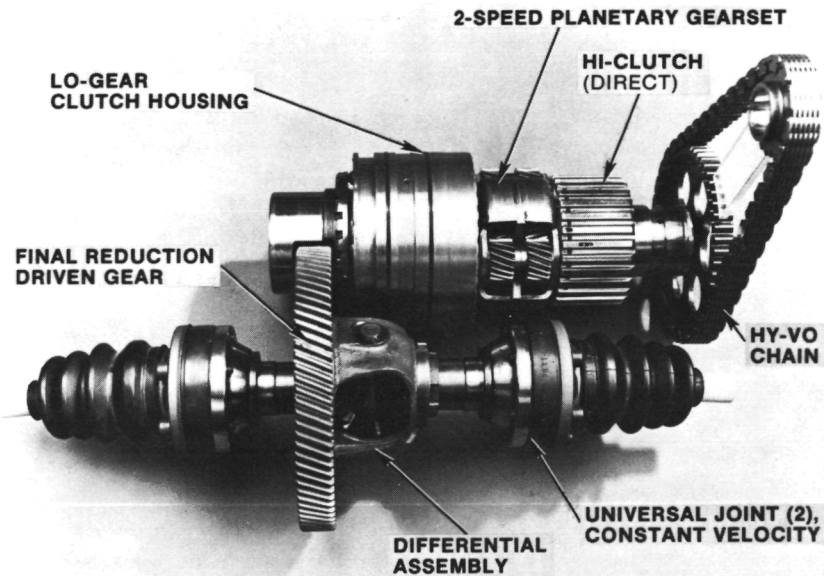


Figure 49. – Performance of an automatic transmission with lockup and a four-ratio manual transmission. Constant input torque: E (automatic with lockup), 136 N-m (100 lb-ft); F (four-ratio manual), 122 N-m (90 lb-ft).

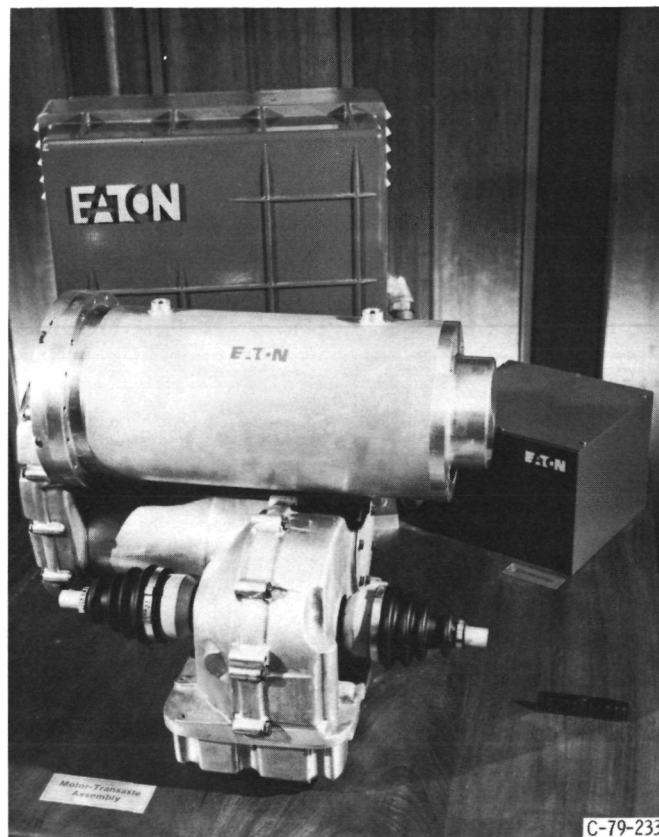
Electric vehicles are energy limited in that they cannot be rapidly refueled as internal combustion engine cars can. Therefore emphasis must be placed on transmitting energy to the wheels in the most efficient manner while still providing acceptable performance. As can be seen from this brief discussion, automotive automatic transmissions can be a cause of appreciable power, and energy, loss. Clearly, more efficient automatic transmissions would hasten the time when electric vehicles become commercially feasible transportation options.

**Automatically shifted electric vehicle transmissions.** – The motor in most electric vehicle propulsion systems can be readily controlled from shaft standstill to maximum rotational speed. Therefore there should be no need for a slipping junction, such as a clutch or hydrodynamic torque converter, in the mechanical portion of the propulsion system. An automatically shifted discrete multiratio transmission should provide the desired convenience and performance with the efficiency of a “manual” automotive transmission. Although such automatically shifted transmissions are not available now, the DOE E&HV program has included their development and demonstration.

The ac induction motor propulsion system being developed by Eaton includes an automatically shifted two-ratio transaxle. The phase I version of this transaxle, shown in figure 50, is a near-term development and could be used with almost any motor. In addition to its function of transmitting mechanical power from the motor to the drive wheels, it also serves as a motor mounting and provides a source of cooling oil for the motor. This transaxle is designed for use with a 9000-rpm



C-82-2421



C-79-2337

Figure 50. — Internal and external views of Eaton phase I automatic transaxle.

motor and consists of a quiet chain-drive reduction gear on the input side, a planetary gear and clutch assembly, a final drive gearset, and a differential assembly. The chain-drive reduction was selected for high efficiency,

low noise, high power-to-weight ratio, and low cost. The gearset and clutch components were adapted from current automatic transmissions. Tests indicate efficiencies from 89 to 95 percent over a broad operating

range for the test model of this transmission. It weighs approximately 48 kg (105 lb). Further details are given in reference 30.

In follow-on work at Eaton the induction motor has been redesigned to have a maximum speed of 12 500 rpm rather than the 9000 rpm of the first motor, and the transaxle design has been refined to use a coaxial shaft concept. This second design, shown in figure 51, reduces size, weight, and potential manufacturing cost. A three-ratio version of the transaxle is also being developed by Eaton as part of a propulsion system that uses a limited-speed, low-cost dc shunt motor. This dc motor has a maximum speed of about 4500 rpm, and chain reduction is used between it and the transaxle input. In these transaxles, gears are synchronized through controlled, rapid changes in motor speed.

The results of these development efforts on automatic transaxles thus far indicate that the technology for high-efficiency, automatically shifted transmissions is ready. For example, the Ford Motor Company and GE are developing an advanced integrated ac power train as part of the DOE E&HV program. This power train features an oil-cooled motor integrally housed in a multiratio automatic transaxle. See figure 52 for the preliminary design layout. Suitable electric vehicle transmissions can be developed for production when a market is identified. In the meantime, they will remain costly because of the need for custom design and few-of-a-kind volume.

## Continuously Variable Transmissions

The limited use of continuously variable transmissions in passenger cars has hindered their application to electric vehicles. CVT's were quite popular with designers of early automobiles, but this popularity was relatively short lived. Improvements in the shifting characteristics of

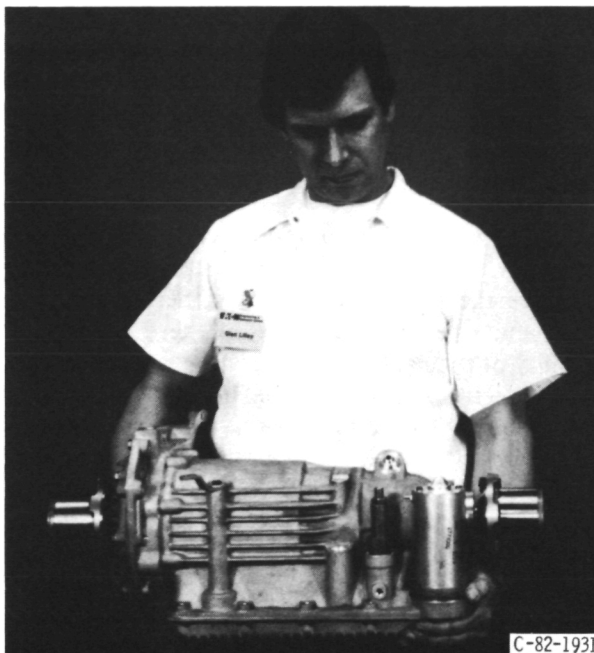


Figure 51. — Eaton phase II automatic transaxle.

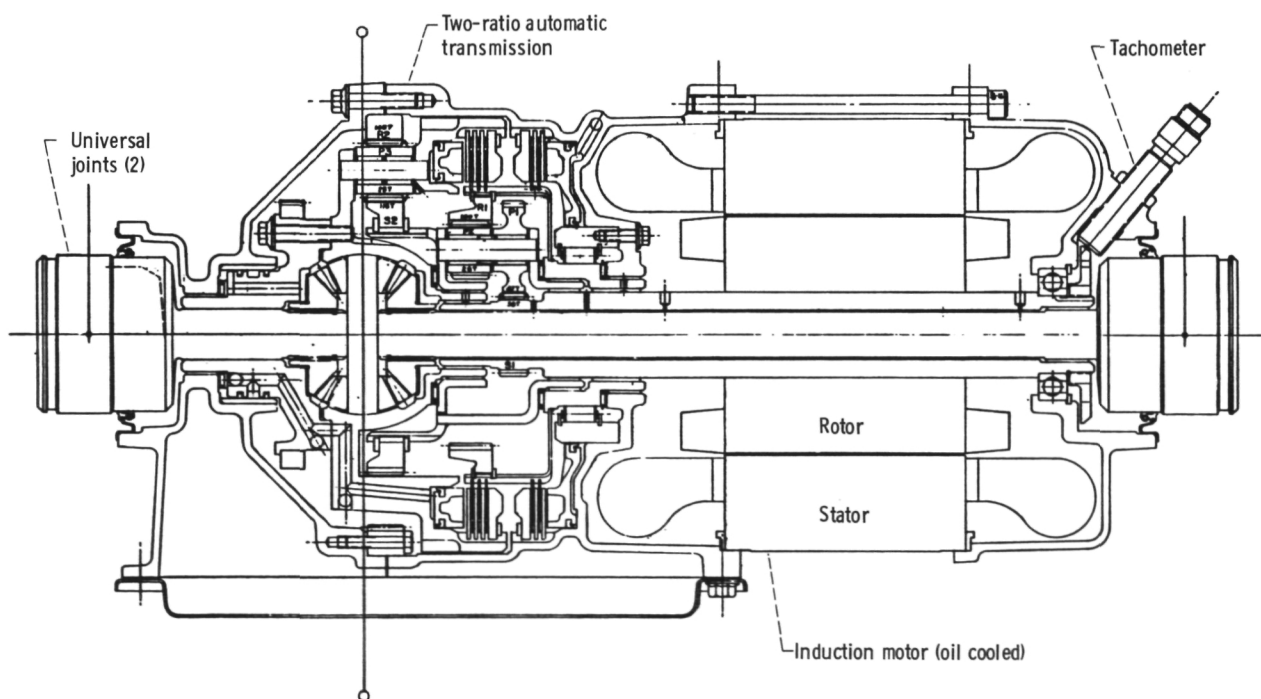


Figure 52. — Ford/GE integrated motor-automatic transaxle.

manual gearboxes in the late 1920's lessened the incentive to develop improved CVT's. Through the years there have been occasional attempts, both here and in Europe, to commercially introduce CVT's into passenger cars. Several of these efforts proved technically feasible, but they were never really serious contenders to replace the automatic, torque-converter, gearshift transmission that was introduced in the late 1930's. Up until the 1970's, the primary emphasis for automatic transmissions was on transmission shift quality and cost; efficiency was basically a secondary consideration. In recent years the emphasis has changed to improving drivetrain efficiency. The CVT's "infinite" number of shift points offers the designer the greatest possible latitude in optimizing the drivetrain.

For electric vehicles equipped with flywheels, some form of CVT is needed to continuously regulate the speed and hence the torque delivered by the flywheel to the vehicle and vice versa. Because of the quick discharge capability of the flywheel, acceleration performance of a flywheel electric vehicle can equal or exceed that of a heat engine vehicle. The ratio range requirements of a CVT for a flywheel vehicle are typically greater than for a vehicle without a flywheel since the flywheel might be operating at some minimum speed while the vehicle is at some maximum speed and vice versa. This is more demanding on the CVT than its use in a conventional electric vehicle where the motor has a wide speed range and the speed of the motor tends to increase with vehicle speed. These factors have triggered renewed interest in CVT's.

There is a large variety of CVT concepts: variable-ratio pulleys with rubber V-belts, variable-ratio pulleys with metal V-belts or chains, hydraulic and hydromechanical systems, and a variety of traction concepts. Reference 52 contains an excellent description of these various concepts. Several of the more promising CVT concepts have been investigated in the DOE E&HV program by means of design studies and one hardware development effort. The detailed results of the design studies are given in references 15 and 53 to 55. Designs using toroidal and cone-roller traction concepts, a steel V-belt concept, and a new flat-belt concept were prepared for a 1700-kg (3740-lb) vehicle with an energy storage flywheel. These designs are shown in figure 53. A flywheel electric vehicle system is a logical choice for a CVT study because not only is some form of CVT an absolute necessity, but also the selected CVT must have a particularly broad ratio range. In these studies the speed ratio of the CVT was to be continuously controllable from flywheel speeds of 14 000 to 28 000 rpm to transmission output speeds of zero to 5000 rpm. However, as an option, the minimum CVT output speed could be 850 rpm with a slipping clutch element on the output side of the CVT to drop the speed from 850 rpm to zero. For the 850-rpm minimum output speed the CVT's ratio range is 11.8:1. In addition,

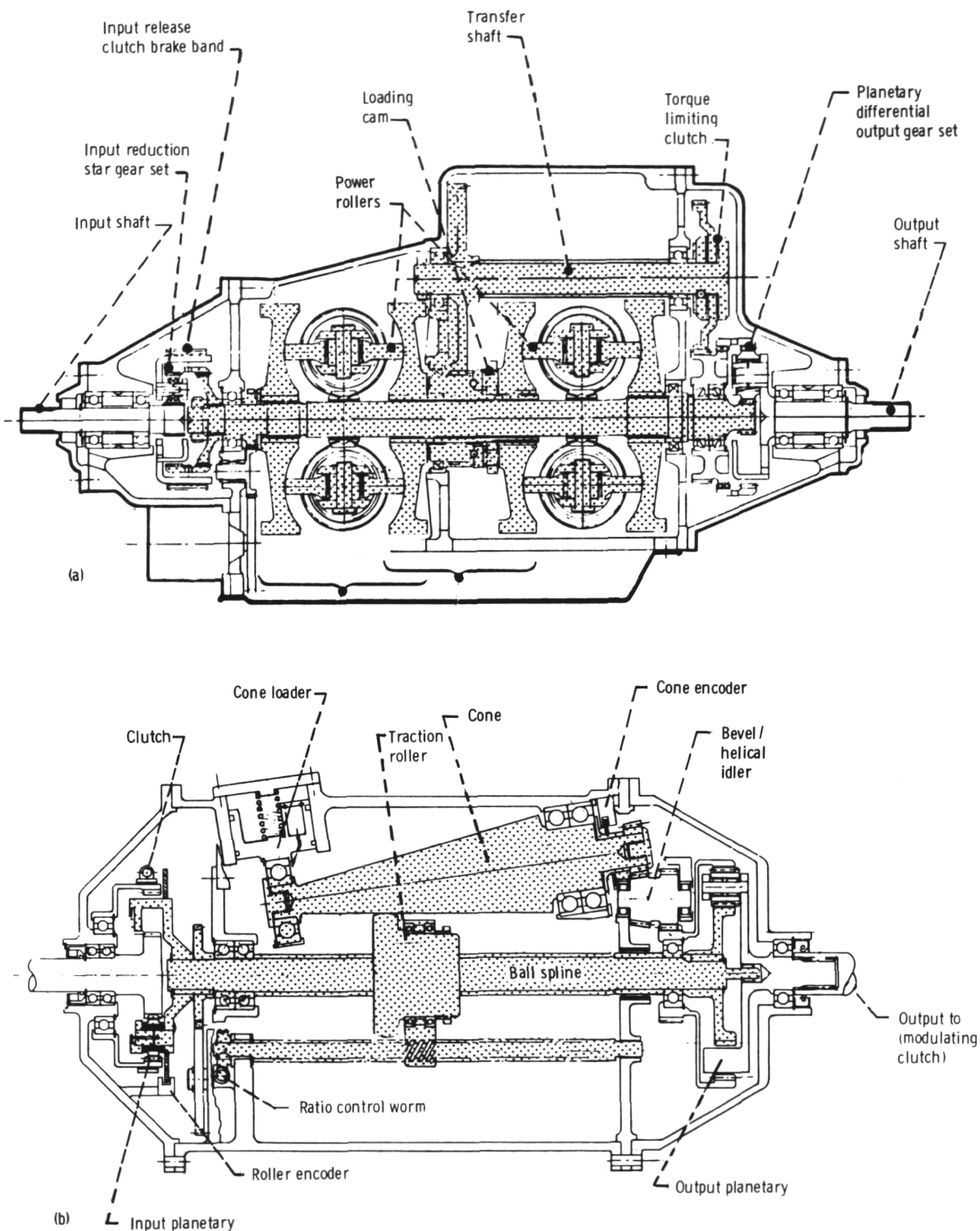
the CVT was to be capable of bidirectional power flow for flywheel regeneration during braking, have a means to engage and disengage the flywheel, and be capable of handling normal driving shock loads. The CVT did not need reverse rotation capability since the electric motor could be reversed to back the vehicle.

CVT's can also be considered for use in electric vehicles without flywheels to optimally match motor speed to load requirements. In this use they would generally need less ratio range than when used with a flywheel.

There are many similarities between the parts for the investigated CVT's and present automatic transmissions. Machining and processing techniques for the unique CVT components are, or will be, well established by the time production commences. It is therefore expected that costs per pound for the CVT's in volume production would be similar to or only slightly higher than those of present automotive automatic transmissions.

**Traction CVT's.**—In a traction CVT, speed ratio is generally varied by changing the relative rolling radius of two contacting elements such as disks, cones, or balls. Torque transfer is mainly accomplished by shear forces generated between smooth driving and driven rollers across an extremely thin film of a special lubricant. Under the high pressures and shear rates that exist in a typical traction contact, the lubricant's viscosity increases dramatically and the lubricant is thought to transform into a plastic-like material. This thin, stiff plastic film can tolerate relatively high amounts of torque transfer without rupturing while protecting the rolling surfaces from appreciable metal-to-metal contact or wear. The failure mechanism of a well-designed traction drive is generally one of rolling-contact fatigue, which is analogous to pitting failure in gears and spalling failure in ball and roller bearings. The torque capacity of a given traction drive is a function of its fatigue life and its construction, that is, its contact geometry and number of contacts working in parallel to share the load. With today's metallurgically clean bearing steels that offer superior fatigue resistance and improved synthetic traction lubricants whose higher coefficients of traction allow a reduction in contact pressure, modern traction drives have considerably more power capacity than their earlier counterparts. Coupling these advances to the greater emphasis on improving fuel mileage and the downsizing of both cars and engines, it is not surprising that there has been a resurgence in research and development on traction CVT's for cars. The DOE program included designs of two traction CVT's: toroidal and cone-roller. These are summarized here, and described in detail in references 53 and 54.

**Toroidal traction CVT:** The preliminary design layout of AiResearch's toroidal traction CVT is shown in figure 53(a). The double-cavity toroidal drive, containing two power rollers per cavity, is permanently connected to

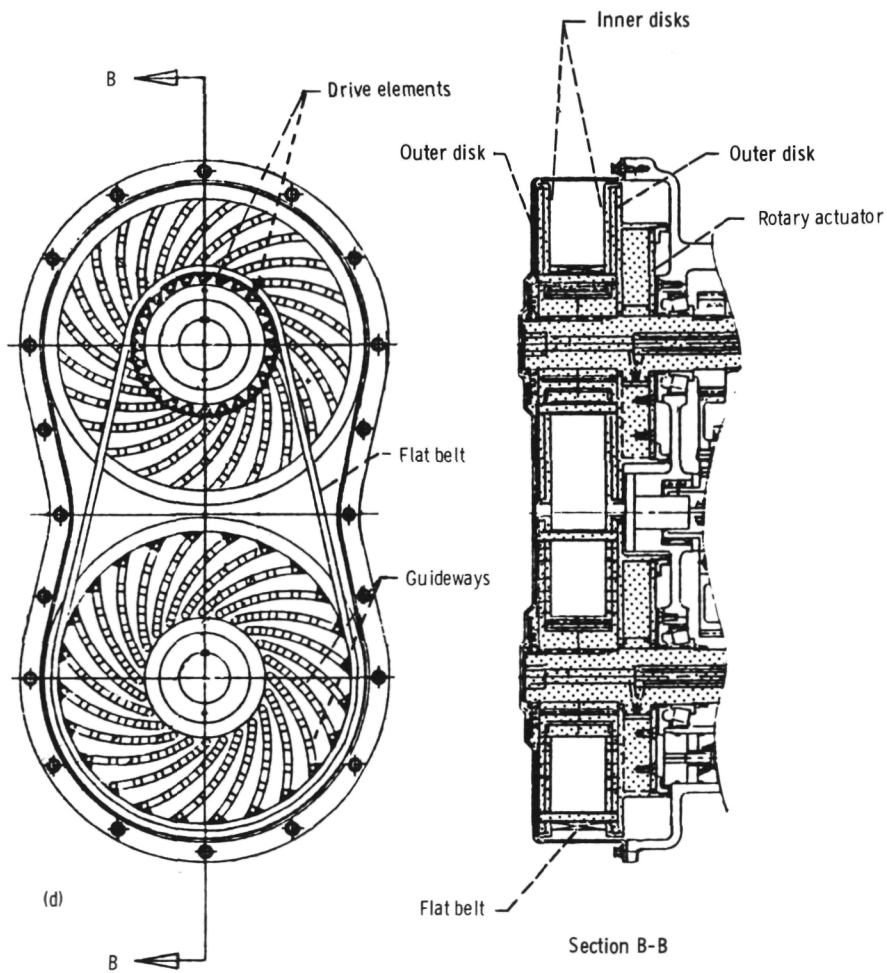
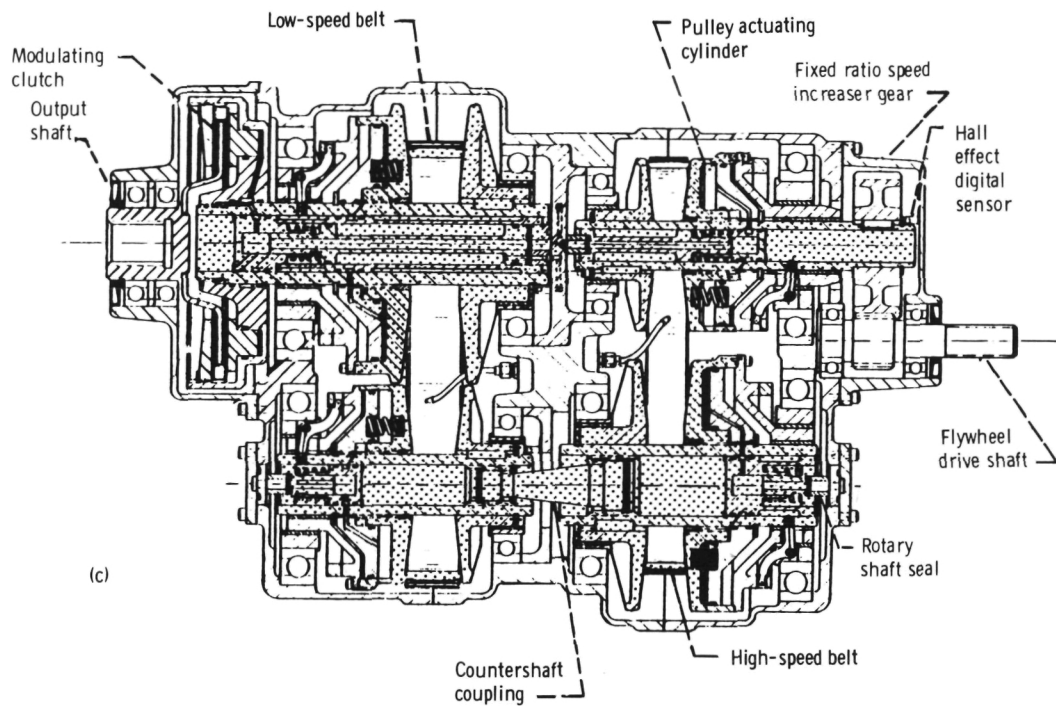


(a) AiResearch toroidal. (b) Bales-McCoin cone-roller.

Figure 53. — Continuously variable transmission study concepts.

differential gearing to form a single mode, power “recirculating” CVT. The differential gearing expands the 5.8:1 ratio range of the toroidal drive section to cover the zero to 5000-rpm output speed requirement of the

study. The input shaft, through the input reduction gearset, drives the two outer toroids and the sun gear of the output differential. The tilting of the power rollers varies the speed of the inner toroids, which are connected



(c) Battelle steel V-belt. (d) Kumm flat belt.

Figure 53. - Concluded.

to the ring gear of the output differential via the transfer shaft. The power that is recirculating between the toroidal cavities and the output differential is always somewhat greater than the output power. A mechanical loading cam mechanism automatically increases the clamping force between the rollers and toroids in proportion to the transmitted torque. This insures that the traction contact will always have sufficient load to prevent slip while minimizing contact overloading under light torque conditions. The CVT ratio is controlled by a pressure-balanced hydraulic control system. This system "steers" the power rollers into a new "tilt" position when the command pressure acting on the roller's reaction piston is not exactly balanced by the traction forces acting on the roller. The estimated weight of this CVT is 63 kg (137 lb) and its efficiency is predicted to be 90 to 92 percent for most driving conditions.

**Cone-roller CVT:** The mechanical arrangement of the Bales-McCoin cone-roller traction CVT is shown in figure 53(b). In this design the variable-ratio traction assembly is connected to an output planetary differential through a set of bevel/helical idler gears. As in the prior example, there is an output differential that expands the approximate 3.6:1 ratio range of the traction roller assembly to achieve output speeds from 5000 rpm down to 850 rpm. A modulating clutch (not shown) is used to attain output speeds down to zero. The traction assembly consists of a central traction roller surrounded by four cone rollers whose axes are inclined. By inclining the cones, their inner contact surface is made parallel to the axis of the roller. The worm-screw drive axially positions the central roller to change the speed ratio. Bevel gears attached to the end of the cones drive the ring gear of the output planetary through the idler gears. The sun gear of the planetary is driven by the input shaft, which is part of the traction roller ball spline. The output shaft is connected to the planet carrier. The cones are loaded against the central roller with individual hydraulic pistons. The hydraulic pressure, and hence contact load, is to be regulated to attain the minimum load needed to prevent significant roller slip at any given operating condition. The estimated weight of this CVT is 32 kg (79 lb), and its predicted efficiency for most driving conditions is between 86 and 92 percent.

**Steel V-belt CVT.**—A preliminary layout of Battelle's steel V-belt CVT designed in the DOE program is shown in figure 53(c). This transmission, described in detail in reference 15, uses a two-stage, steel V-belt system of the compression type to achieve the minimum required ratio range of 11.8:1. An output modulation clutch is used to lower the output speed from 850 rpm down to zero and to provide overtorque protection. A 2.8:1 spur gearset reduces the flywheel speed entering the high-speed belt. The belts are only used as reducers, varying from about 1:1 to 1:3.9 for the high-speed belt and from 1:1 to 1:3.3 for the low-speed belt. A microprocessor-controlled

hydraulic system controls belt shifting and regulates the axial clamping force between pulleys to achieve the best compromise between drive efficiency and belt life.

Battelle's steel V-belt concept had received some early hardware development by Battelle Columbus Laboratories in the 1960's. The construction of their belt is similar to that of the van Doorne V-belt. It is composed of a stack of solid struts gathered together by a nested set of thin, steel bands. Because the bands lie freely on the top of these struts, relative motion is possible between the individual bands themselves and also between the band set and the struts. The ends of the struts contact the face of the V-shaped pulleys. This type of belt is termed a "compression belt" since the driver pulley pushes the driven pulley through the stack of struts. The set of bands keeps the struts from buckling. Consequently, the bands carry high tensile forces and are subjected to high bending stresses as they travel around the pulleys. It is basically the bending fatigue strength of these bands that sets the torque capacity and minimum pulley diameters (or the ratio range) of the drive. Also, since the bands slide over each other and over the struts as the belt moves, proper lubrication and material selection are important to prevent destructive surface galling. The estimated weight of this CVT is 70 kg (154 lb). It is the heaviest of the four concepts studied but also the best known and understood. Its predicted efficiency for most driving conditions is 92 to 96 percent. The steel V-belt CVT is being extensively developed by U.S. and foreign organizations for use in internal combustion engine passenger vehicles.

**Flat rubber belt CVT.**—The variable-pulley-diameter, flat-rubber-belt CVT concept of Kumm Industries is shown in figure 53(d) and is described in detail in reference 55. The flat belt is in contact with a set of drive elements. The ends of these drive elements are contained in guideways or circular arcs that have been machined in a pair of inner disks and a pair of outer disks, but in opposite directions. The radial position of these drive elements, and hence the pulley diameter, is determined by the intersection of the inner-disk guideways, which are curved one way, and the outer-disk guideways, which are curved in the opposite direction. As the inner and outer disks are rotated relative to one another by a hydraulic rotary actuator, the drive elements are moved radially in and out, changing the drive ratio. A hydraulic control circuit used to control the actuator also provides sufficient belt tension to prevent slippage without overloading. The two variable-diameter pulleys are used in combination with differential gearing (not shown) to achieve the required speed variation. The differential gearing is used only in the "low" speed mode to attain zero-output rpm while the 4:1 ratio range (2:1 to 1:2) of the pulleys is used in "direct" drive to achieve maximum vehicle speed in the "high" speed mode. The "low" and "high" speed modes are separated by synchronous

clutching. Stepdown gearing from the flywheel insures that the pulley speeds never exceed about 10 000 rpm. The estimated weight of the Kumm CVT is about 44 kg (97 lb) and its predicted efficiency for most driving conditions is 90 to 97 percent.

Of the four concepts investigated in the DOE E&HV Propulsion Development Project, only this flat-belt concept had not been previously built and tested in some form. Because of this and the predicted high efficiency of the flat-belt concept, the variable-speed element of the Kumm CVT has been built and tested. The resulting test hardware is shown in figure 54. Results of initial tests of this transmission show efficiency in the 90 to 95 percent range for output torques of 100 to 400 N-m (136 to 542 ft-lb), where output power ranged from 14 to 65 kW (18 to 87 hp).

**Other CVT's.** – Although not included in the DOE E&HV Propulsion Development Project, several other CVT concepts have been or are being considered for automotive use by other organizations. These are discussed here.

**Rubber V-belt CVT's:** Variable-speed rubber V-belt drives have been used on low-power vehicles such as snowmobiles for many years. They appeared briefly on early automobiles at the turn of the century along with variable-ratio friction drives. Their simplicity relative to

other types of speed changers makes them attractive for automotive service, where periodic belt replacement can be tolerated. The only automobile being mass produced today that is equipped with a CVT has a rubber belt transmission. The car is the Volvo 343, a medium-size sedan weighing about 900 kg (1980 lb). Its twin rubber V-belt transmission, referred to as the Variomatic, has a ratio range of 3.7:1 and transmits a maximum of 52 kW. The design of this transmission is at least 20 years old. It was originally developed in Holland for use on the DAF 66 introduced in 1972. Rubber V-belt drives have also been applied to electric vehicles. The Waterman DAF sedan powered by a 6.7-kW dc series motor is one example (ref. 1). For small, relatively low-power vehicles, the rubber V-belt CVT offers the combination of relatively low cost and efficient operation. Average efficiencies in the low 90's can be expected. However, durability limitations hamper the application of these CVT's to larger vehicles. The DAF and Volvo approach of combining two V-belt drives in parallel raises acceptable power limits at the expense of added cost and complexity. Average service lives of 40 000 to 50 000 km (25 000 to 31 000 miles) for these medium-size vehicles are not uncommon, and the technology of rubber V-belt construction is continuously being improved.

**Chain CVT's:** Although variable-speed chain drives are basically industrial in nature, they have been evaluated for automobile applications. One example is a test program conducted by GKN Transmission Ltd. in England (ref. 52). Tests were conducted on a front-wheel-drive car equipped with a continuously variable PIV (manufacturer's name) variator made in West Germany. The PIV variator consists of a chain whose links are connected by smooth, round-ended pins that are trapped between two smooth-faced, V-shaped pulleys. Speed ratio is varied in the same manner as any other V-belt drive. Efficiencies in the 85 to 90 percent range could be expected for specially designed chain CVT's.

**Hydraulic and hydromechanical CVT's:** Hydraulic variable-speed drives have a long history of use in vehicles. Hydrostatic (variable-speed pump and motor) drives are used extensively in construction and off-the-road vehicles because of their durability and their ability to handle high power in a small package. Their relatively low efficiency and high noise makes them unsuitable for passenger-carrying automobiles without the addition of power-splitting mechanical gearing to minimize the power transmitted hydraulically. Even with power-splitting gearing, hydromechanical units tend to be less efficient and considerably noisier than other types of CVT's. On an electric vehicle the hydraulic noise would be troublesome. However, with a hydraulic transmission it is relatively straightforward to add an energy storage system in the form of hydraulic accumulators. Because

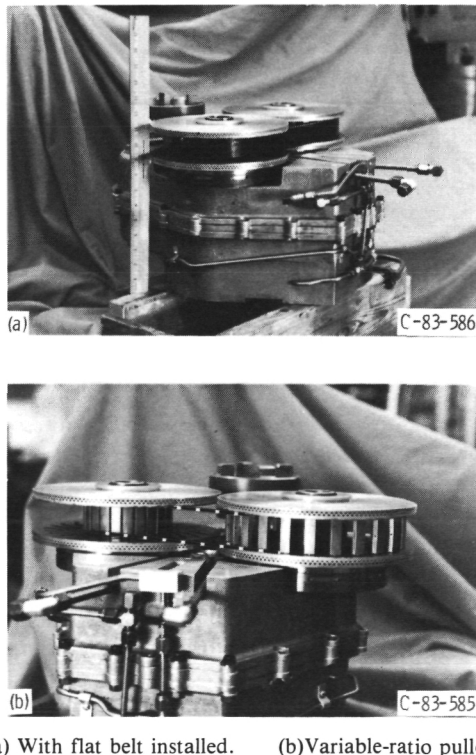


Figure 54. – Kumm experimental continuously variable transmission variable-speed assembly.

hydraulic accumulators tend to be relatively heavy, such a system best lends itself to a larger vehicle such as a bus.

### Status of CVT Technology

CVT technology has shown slow but steady progress through the years. Increasing concern over our diminishing petroleum resources, coupled with recent technological advances in materials and design techniques, has hastened the likelihood that a commercially viable, automotive CVT will be produced. Some of the CVT designs reviewed are already nearing the point of commercial acceptance, and undoubtedly there will be improvements with time. The CVT field also offers plenty of opportunity for innovation.

In the case of electric and hybrid vehicles, CVT's can be beneficial, provided they are efficient, reliable, and not too costly. In the case of flywheel-equipped electric vehicles, some means to transfer energy between the flywheel and the drive axle, such as a CVT, is a necessity.

In assessing the general level of CVT technology, it appears that the basic technology is in hand to make most CVT's functional. However, power limits, cost, and reliability factors are largely unknown. Furthermore, identification of critical technology elements where improvements can be obtained is warranted. Each of the CVT types, given sufficient development, would provide satisfactory operation on a battery electric or hybrid electric vehicle, although some are obviously more desirable than others. In this regard, the belt and traction designs look particularly promising for advanced electric vehicle CVT applications, with belt drives appearing somewhat nearer term.

### ENERGY STORAGE DEVICES

A short-term energy storage device has been included in some electric vehicle propulsion system designs to absorb energy during deceleration and later release it to provide the peaks of power needed for acceleration. The goal of such a design is (1) to provide improved acceleration, (2) to increase the overall system efficiency by leveling the load on the battery, and (3) to act as a secondary source of stored energy. Energy storage devices can be flywheels, pneumatic or hydropneumatic accumulators, or mechanical or elastomeric springs. In general, all such devices require some input-output means. The type of input-output means varies with the type of storage device (CVT's for flywheels, pump-motors for accumulators, etc.) and, in general, adds complexity and weight to the propulsion system. The use of energy storage devices in electric vehicle propulsion systems has been investigated extensively in the energy storage part of the DOE Electric and Hybrid Vehicle Program and by others in industry and universities. The reader is referred to the literature (ref. 56) for sources of

information on flywheel energy storage. In general, the flywheel has been recognized as the most promising form of storage device. The other devices may also be attractive because they may not need the degree of technology advancement that flywheels need. Because of this, a brief study of alternative energy storage devices was conducted by Honeywell as part of the Lewis-managed E&HV Propulsion Development Project (ref. 57).

In the Honeywell study, various energy storage concepts were considered for a 1360-kg (3000-lb) electric vehicle using lead-acid batteries and operating repeatedly over the SAE J227a Schedule D driving cycle. They were

- (1) Hydropneumatic (liquid/gas)
- (2) Pneumatic (gas)
- (3) Mechanical (springs)
- (4) Momentum (flywheel)

For trade-off purposes all four concepts were considered initially. However, because significant development effort was already under way with flywheels, this concept was barred from being selected for final design analysis.

From the assessment and subsequent storage device trade-off evaluation, a hydropneumatic (liquid and gas) concept was selected for design. The significant components in this concept are the hydropneumatic accumulator and hydraulic motor-pump. Vehicle energy is stored during braking by compressing gas in the hydropneumatic accumulator with a hydraulic pump. Energy is provided during acceleration by discharging the stored energy in the accumulator through the hydraulic motor into the drivetrain.

Detailed analysis of this concept using actual manufacturer-supplied data for weights and efficiencies shows that this concept yields only a 5-percent improvement in vehicle range (as compared with a straight electric vehicle) if commercial, currently available motor-pumps and near-term-available lightweight, fiber-wrapped accumulators are used. With the assumption of reasonable improvements in the weight and efficiency of the required hydraulic machines, a 19-percent increase in range was predicted for a vehicle operating over the SAE J227a Schedule D. The hydropneumatic system, however, would increase the vehicle weight by 100 to 150 kg (220 to 330 lb). Tests on a delivery van with a hydraulic storage system (ref. 58) indicated a 10-percent increase in range over the Schedule B and a 30-percent increase over the Schedule C driving cycles of SAE J227a. Projections of range increase through the use of electrical regeneration are comparable to the predicted 19-percent increase with the hydropneumatic system.

Since a storage device increases the complexity of a propulsion system, its inclusion must be weighed against using electrical regeneration and increasing the battery

weight for additional range or increasing the power capability (and weight) of the propulsion motor and controller for increased acceleration. The mission of the vehicle (e.g., delivery van or stop and go) must be considered in this evaluation.

The literature often includes battery life as a factor when energy storage devices are considered for inclusion in a propulsion system. The battery load leveling provided by the device is expected to result in increased battery cycle life. To obtain some experimental data, statistically designed life-cycle tests were conducted by the Naval Weapons Support Center in Crane, Indiana, for the E&HV Propulsion Development Project. In these tests three types of batteries were subjected to discharge profiles simulating three different propulsion systems. The batteries were the EV-106, representing present electric vehicle batteries; the EV-1000, representing improved flat-plate lead-acid batteries; and the 3KQ11, representing tubular positive lead-acid batteries intended for load-leveled service. The three discharge profiles were based on the SAE J227a Schedule D driving cycle and simulated (1) an electric propulsion system with no regeneration, (2) a system with electrical regeneration, and (3) a system having energy storage that drew constant current from the battery when the vehicle was in motion. The results of these tests indicate that regeneration and load leveling may have little, if any, effect on the life of properly designed and maintained lead-acid batteries. These results suggest that energy storage may not be the best means of extending vehicle range. Rather, additional batteries equal in weight to that of the intended storage system, together with electrical regeneration, might be best for range extension. Storage devices, however, because of their high power capability could enhance vehicle performance without undue battery, motor, or controller stress.

## Technology Needs

Although the range of an electric vehicle is primarily a function of the energy available from the battery, the weight and efficiency of the vehicle's propulsion system also have an effect on range. As compared with present dc systems of equivalent efficiency, a lightweight propulsion system with the same battery technology can (1) allow reduced total vehicle weight and thereby, a somewhat increased range, (2) allow use of more battery weight, again increasing range, or (3) allow the same range as the dc system but with a lighter lower cost vehicle and less battery weight. Increasing efficiency results in better utilization of battery energy to propel the vehicle. This has benefits similar to reduced weight. Acceptable acceleration can be obtained with today's dc motor technology but at unacceptably high weight. The cost of propulsion systems with today's dc technology

will probably remain unacceptably high, even in volume production, because of the dc motor's complexity and size.

The improved and advanced technology for efficient, lightweight electric vehicle propulsion has been demonstrated with a variety of new developmental propulsion components and systems. This new technology can result in the range and performance improvement predictions indicated in figures 8 and 9. It also has the potential for acceptably low cost when fully developed and used in volume production. However, the present cost of propulsion hardware based on the new technology is generally too high for commercial feasibility. This cost problem is a result of materials and components that are costly, have low production volume, and use complex electronic assemblies.

The essential barrier in propulsion systems to achieving the goal of the DOE Electric and Hybrid Vehicle Program is then the cost of the hardware that incorporates improved or advanced propulsion technology. The technology needs for electric vehicle propulsion systems and components can be summarized quite simply: technology that will reduce the cost of vehicle ownership while maintaining the weight, efficiency, and performance of the demonstrated new technology. The effort needed to provide the basis for satisfying this primary need is described in the remainder of this section.

Mass-produced induction motors for electric vehicle propulsion should have an OEM cost that is less than half the cost of a conventional brush-commutated dc motor. The more efficient permanent magnet motors may be somewhat more expensive than the induction motor, but estimates indicate that the OEM cost of a permanent magnet motor could be between \$200 and \$300 when production volume reaches 100 000 units per year. However, research and development of high-energy permanent magnets must continue in order to achieve this reduction in propulsion motor cost. The cost of the finished magnets must be lowered through new and improved fabrication techniques and formulations that require less of the critical and costly materials.

The electronics are, without question, the most expensive part of the attractive induction motor and electronically commutated motor propulsion systems. However, it must be kept in mind that these electronics contain virtually all of the control functions that are likely to be required for motor operation in an electric vehicle. The present OEM volume cost of these electronics has been estimated at \$1400 to \$1650 for the thyristor versions. The transistor electronics cost is considerably higher now, but is potentially less expensive due to the less complex circuitry required. Because of increased industrial needs, such as process control in the chemical industry, there has been more interest recently in low-cost, high-power transistors by many major

transistor manufacturers. However, the needs of electric vehicle propulsion require that semiconductor development aimed specifically at volume automotive production be pursued. Present technology uses individual power semiconductor components connected together in carefully laid out assemblies. These assemblies represent a relatively large cost in manpower as compared with the assembly of an induction motor. Research and development are needed to provide integrated power semiconductor assemblies that can be machine made. Possibly, integration of the complete inverter power stage semiconductor complement on a single chip, or in a single hybrid package, can be realized. This will require the solution of problems in power semiconductor fabrication techniques and in heat removal and temperature control methods. These are formidable problems and the necessary technology advance will require 5 to 10 years.

Another means of cost reduction is component and system simplification. This simplification is not solely in the control logic because logic circuitry can be reduced to integrated circuits when volume production is needed. Rather, the number and complexity of power-handling devices must be reduced. The following are some suggested courses to simplification:

- (1) Development of simple motors such as the reluctance motor and its unipolar power controller
- (2) Development of integrated power semiconductor assemblies
- (3) Development of a simple, continuously variable transmission for flywheel-assisted propulsion
- (4) Development of integrated power train assemblies

There does not appear to be any outstanding barrier to economically practical electric vehicle propulsion systems beyond those outlined above. However, design for volume production will certainly be a very formidable engineering task. Development of new production techniques and machinery will be a necessity. But, if a volume market for electric vehicles is perceived and volume production is set as a goal, costs will certainly be reduced and become more acceptable.

In summary, technology to reduce cost is the foremost need. Detailed development and volume production should result in reasonable costs with existing demonstrated technologies. Simpler propulsion systems will enhance the competitive position of electric vehicles through higher reliability and perhaps lower cost. This would require further work on one or more concepts, such as the reluctance motor. The required technology for this motor system would probably not be available until the late 1980's. The ultimate in low-cost power electronics, integrated power circuits, could possibly be available in the 1990's if such development is vigorously pursued.

## Concluding Remarks

Since 1976 the NASA Lewis Research Center has been responsible for the propulsion system technology development portion of the DOE Electric and Hybrid Vehicle Program. The subsequent 7 years of propulsion technology development included evaluation of existing commercially available technology, extensive analytical studies, and the development of technology for improved and advanced motors, controllers, transmissions, and complete propulsion systems. The accomplishments of these activities and their potential effect on the future direction of electric vehicle technology development efforts are thoroughly presented in this report. A brief summary of these accomplishments, a few of the major findings, and their significance follow:

1. In comparing propulsion technology three factors are important: weight, efficiency, and cost.
2. Propulsion component technology advances in motors, controllers, inverters, and transaxles result in component efficiencies in the low to mid-90 percent range.
3. Integration of the best of these components into complete propulsion systems yields system efficiencies of 75 to 80 percent and represents an efficiency improvement of 30 percentage points over 1976 systems.
4. System weight reductions of approximately 25 percent have been achieved in the past 7 years.
5. These improvements are expected to nearly double the range of an urban electric car using a given battery.
6. Along with the expected increase in range, these improvements provide an acceleration equivalent to that of a diesel engine car. Further improvement in acceleration will come at the expense of propulsion system efficiency and weight unless flywheel technology is used.
7. Further major efficiency improvements in propulsion systems are not likely and therefore substantial improvements in vehicle range must come from advances in battery technology.
8. The battery power and energy requirements to achieve various ranges and accelerations for both current and advanced propulsion systems are presented. These results should be useful in establishing battery performance goals for future battery research efforts.
9. Successful technology development efforts directed at cost reduction were achieved. Actual costs must wait until manufacturing cost assessments can be generated that are consistent with the scale and method of production appropriate to the automotive industry.
10. With continued power electronic advances coupled with the ongoing development of inverter systems for both industrial applications and electric vehicles, the cost of an ac propulsion system is expected to decrease to the point that it will become the system choice for advanced vehicles.

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1. Report No. NASA TM-83504		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle  Electric Vehicle Propulsion Alternatives				5. Report Date November 1983	
				6. Performing Organization Code 778-36-06	
7. Author(s)  Richard R. Secunde, Richard M. Schuh, and Raymond F. Beach				8. Performing Organization Report No. E-1845	
				10. Work Unit No.	
9. Performing Organization Name and Address  National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135				11. Contract or Grant No.	
				13. Type of Report and Period Covered Technical Memorandum	
12. Sponsoring Agency Name and Address  U.S. Department of Energy Office of Vehicle and Engine R&D Washington, D.C. 20545				14. Sponsoring Agency <del>Code</del> Report No. DOE/NASA/51044-33	
15. Supplementary Notes  Final report. Prepared under Interagency Agreement DE-AI01-77CS51044. Reprinted in part as NASA TM-83527, Electric Vehicle Propulsion Alternatives - Executive Summary.					
16. Abstract  This report summarizes 7 years of propulsion technology development for electric vehicles. It includes analytical studies, technology evaluation, and the development of technology for motors, controllers, transmissions, and complete propulsion systems. The work was accomplished by the Government and by industry and universities.					
17. Key Words (Suggested by Author(s))  Electric vehicle propulsion Electric vehicle components Electric vehicle simulation				18. Distribution Statement  Unclassified - unlimited STAR Category 44	
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of pages 63	
				22. Price* A04	